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## Book I


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May 2010

To my grandfather José, who unfortunately
had to travel to the other dimension too early

*J. Manuel Feliz-Teixeira*

# "Solar-dam": for Retrieving Energy from the Sun

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March 2010

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KEYWORDS: renewable energy, solar energy, mechanical solar device, solar engine.

**ABSTRACT**

A very simple solar engine is described herein. Since it is a mechanical device, with moving parts, its practical usefulness may perhaps be low, at least compared with the modern systems based on semiconductor solar cells. Nevertheless, due to its extreme simplicity, and as it is easy to build in several formats and dimensions, it deserves to be mentioned and described. It should be considered more as a concept than a completely tested device. At least as a curiosity and as a didactic model we hope it will interest someone. Some home-made versions of the *solar-dam* concept have been built using day-to-day materials, and then minimally tested in order to verify their correct operation. Most of the times those models were behaving as self-oscillating devices, which were automatically starting to operate in the morning, with sunrise, and stopping only at sunset, in the evening. We believe, nevertheless, they may also enter into a complete cycle if properly adjusted. Such a machine may also be used as a dynamic element of architecture, for instance, and surely as a good example of the conversion of sunlight into mechanical energy at ambient temperatures.

## 1. Introduction

It is a fact that solar energy enthusiasts are at the moment passing through a less enthusiastic period, since people around the world are complaining about less and less sunlight reaching the Earth's surface, due to frequent obstruction by an abnormal quantity of man-made clouds dispersed in the skies[1]. The next figure shows a strong case of these types of clouds, as a curiosity. Solar energy seems suddenly to be forgotten, since last year.

**Fig. 1** Man-made type of clouds observed all over the world.

Since I am affected by rhinitis provoked by these clouds, the reader will forgive me if I write a few more lines about this: it is public knowledge that weather experts are detecting a significant increase in the temperature of the planet since, say, 1995, but that data seems to show something "abnormal" that already started in 1920-30[2]. In order to curb such a tendency, some scientists have proposed that our globe should be covered with artificial clouds to reflect 10-20% of the sunlight back to space, therefore reducing the warming affect. Edward Teller, the nuclear physicist closely connected to the

[1] Some people would call this subject a simple "controversy", but the truth is these clouds are extremely well documented all over the world by independent articles and photos and video footage, on the Internet. It is also a mystery that no university around the world seems to be interested in studying the phenomenon, while the media keeps silent about it too.

[2] Read about "global warming" in *wikipedia.org*, for example.

first Atomic Bomb, and the "father" of the Hydrogen Bomb[3], seems to have been one of those who advocated and proposed this solution[4]. It is hard to imagine a human being proposing sinister solutions for humankind, but in fact it would not be new, if true, therefore people should at least get informed about the subject.

The more we use solar energy the less the planet will warm. But one of the most actual issues is not about how to produce clean energy, but instead about questioning what are we doing with the energy we produce. Basically, would it make any sense to spend money and resources generating clean energy when most people would live with open windows during winter, or if such energy would be used for war, for example? How many family houses could be fed, and for how long, by the energy of the simplest Atomic Bomb? Wouldn't it be simpler and more intelligent to close the windows and reduce the astonishing race of the weapon industry? Global *efficiency* seems to be the modern issue, not the production of energy, in our opinion, but our societies are still extremely resistant to understanding this.

## 2. Why "solar-dam"?

This solar system has been named "solar-dam" because it naturally resulted from an association of thoughts concerning the principle of operation of a normal water dam, roughly depicted in figure 2.

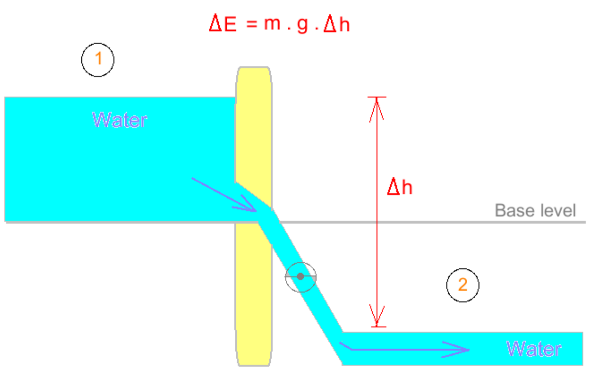


**Fig. 2** Simplistic diagram of a water dam.

It is known that these huge water machines are structures made of two sides. They could be thought of as being made of two reservoirs, interconnected by a tube through which the water flows when energy is to be transformed into electricity. This flow is due to the differential of pressure between the two sides. This pressure comes from gravity, that is, from the difference in gravitational energy between side 1 and side 2. With time (and rain), the reservoir 1 is filled with new water, and the potential energy rises with the increase of the *mass* of the liquid and the *height* above the reservoir 2. The stored energy is simply given by $\underline{\Delta E = m.g.\Delta h}$, $\underline{g}$ being the acceleration of gravity, as we know.

The question that came to my mind when I was around 16[5], was the following: could it be a way of inverting the process after the reservoir 1 is empty, in order to create a sort of oscillating device based on this principle? Around that time the answer appeared to be: yes, that could be done if, after emptying reservoir 1 into reservoir 2, one would elevate the reservoir 2 and lower reservoir 1. That, of course, is difficult to do in a normal water dam, but the process is much simpler to implement when the "pressure" of gravity is replaced by the "pressure" induced by sunlight, as we will see.

## 3. The "solar-dam" concept

Two equal reservoirs are used in the "solar-dam", through which a *constant volume* of a fluid is made to oscillate. In a certain way, this is similar to the concept of the *Stirling engine*[6] due to the fact that the same fluid will forever be maintained in the interior of the machine, and the transfer of heat (thermodynamic energy) into mechanical work is made at each oscillation of the fluid.

In the first version of the "solar-dam", these two reservoirs were made to communicate by separated tubes, one for each direction of flow, allowing the fluid to be transferred from reservoir 1 into the reservoir 2 and vice-versa. Each time the fluid was being transferred mechanical energy was to be produced. To guarantee the cycle of the machine, once the fluid was transferred, the machine was made to invert its position relative to the source of heat (See fig. 3).

[3] http://en.wikipedia.org/wiki/Edward_Teller

[4] Search the internet for the article "*Global Warming and Ice Ages*:"

[5] In effect I have imagined the "solar-dam" around that age, but the very first model, made of balloons of glass, which funnily had exploded in my hands, could not let me be sure if it would really work or simply explode. It is also funny that only some years ago I could return to the idea and verify that it works.

[6] http://en.wikipedia.org/wiki/Stirling_engine

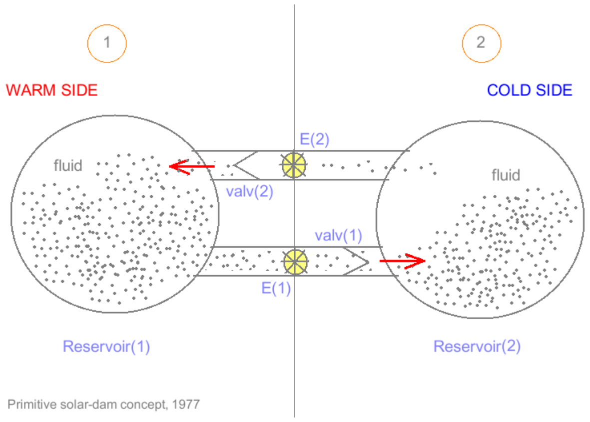


**Fig. 3** The very first solar-dam engine, built of glass.

In this case, the fluid was heated on the side 1, expanded through valve 1 into the side 2, while producing the mechanical energy *E(1)*; once the equilibrium was achieved, the entire system was rotated manually 180º in order to invert the process. It was precisely at the moment I was touching side 1 to warm it with my hand that the machine decided to explode. The calculations where elemental and considered the fluid an ideal gas, with internal energy roughly given by:

$$E_i = P.V = n.R.T_k \qquad (1)$$

Relating pressure (P), volume (V), temperature in degree Kelvin ($T_k$), perfect gases constant[7] (R), and the quantity of material (n) in number of moles.

We may now notice that there are *three* very important *rates* dominating the thermodynamics of this system: (1) the rate at which the energy increases in the warm side; (2) the rate at which energy decreases in the cold side; (3) the rate of transfer of material from one side to the other. To treat this problem in a reasonable way is not so simple, and it is beyond the purpose of this article, but at least we may notice that both the *quantity of material* and the *temperature* in each side are time-dependent functions, and it holds, for any instant of time:

$$n_1(t) + n_2(t) = constant = N_0 \qquad (2)$$

As well as a difference of energies of:

$$E_1 - E_2 = n_1(t).R.T_1(t) - n_2(t).R.T_2(t) \qquad (3)$$

As long as $E_2$ is different from $E_1$, the fluid may move from one side to the other and produce mechanical work. Notice that equation 3 may also be shortened as:

$$(E_1 - E_2)/R = n_1.(T_1 + T_2) - N_0.T_2 \qquad (4)$$

To this, we should now superimpose the *periodic rotation* of the system, which controls both the *time of exposure* to the heat source and the *period* of its cycle. Since it was not easy to make an estimation of the behaviour of the machine analytically, a little simulator have been developed to give us an idea of what to expect from a real system, if it rotates with a certain frequency. For example, the next figure (fig. 4) shows the tendency of the pressure (P) in both reservoirs, as a result of simulation.

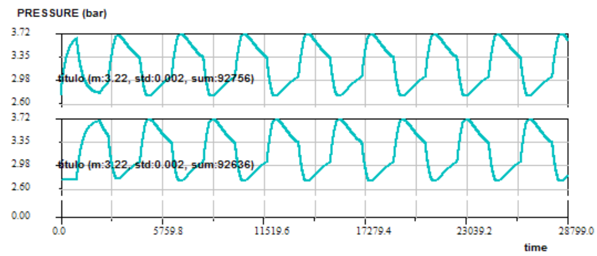


**Fig. 4** Simulation record of the pressure inside recipients.

As one may notice, there is a 180º out of phase between the pressure on the two recipients. The frequency of rotation was previously defined, and in practice it should be chosen in a way to achieve the best performances. Notice that this system is a case of an asynchronous system, and that more complex typologies can be tested, using a different number of recipients, instead of two.

## 4. The synchronous version

Although it also could be interesting to think on an asynchronous machine where the frequency of exposing the recipients to the heat side would be monitored and controlled by a low power computer, the next challenge was to design a practical "solar-dam" which would be self-synchronised by its own levels of pressure, thus without the need for any pre-programmed control. This issue has been

[7] R = 8,314472(15) J.K$^{-1}$.mol$^{-1}$

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reduced to the questions: (1) how to transform the "solar-dam" concept into a practical device with which electrical energy could be produced? (2) how to make the "solar-dam" rotate properly by its own "decision"?

The first problem was to be addressed by using, in each direction of flow, a small turbine connected to an electrical alternator. To improve the efficiency of the process, a second fluid of higher density than the original gas was added to the machine, in order to attack the turbines. Water was used for this purpose due to its low viscosity. The pressure inside each side of the device was planned to be generated by two independent and specially designed solar panels, one pointing in the sunlight direction, the other at the shadowed side. Thermodynamically, one can say that this model would operate between those two temperatures. The entire machine, which had been designed to rotate around its central axis, assumed the aspect shown in the figure:

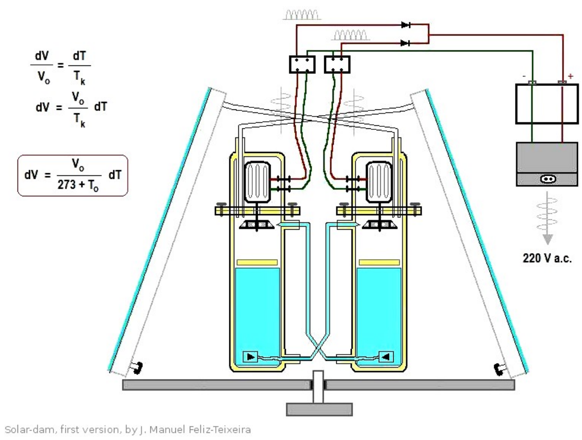


**Fig. 5** First "solar-dam" model, from 2007.

This machine is absolutely symmetrical, as a sort of *gemini* connected to each other. The only requirement in order to start operating is to rotate it properly. Each solar panel contains a gas and each reservoir is previously filled with a certain quantity of water, communicating with the other through a valve and a jet stream of liquid that periodically attacks the opposite turbine. The two electrical generators are independent, connected in parallel after rectifying their signals, and drive a battery bank. No prototype of this idea could, unfortunately, be built, due to the lack of financial support.

The second problem was resolved using the force of gravity. Since the machine changes its center of mass while in operation due to the movement of the liquid, and masses "tend to fall to the center of mass", a slight inclination of the machine from the vertical of the place was enough to make it start oscillating.

## 5. Maximum efficiency

The real efficiency of this machine could not be tested, but it is interesting to try to estimate its maximum value based on the ideal Carnot Cycle efficiency, which depends solely on the absolute temperatures of the warm ($T_{wk}$) and cold ($T_{ck}$) sides, and is given by:

$$eff_{carnot} = 1 - T_{ck}/T_{wk} \tag{5}$$

Or, considering the temperature difference:

$$T_{wk} - T_{ck} = \Delta T$$

by:

$$eff_{carnot} = \Delta T / T_{wk} \tag{6}$$

During some tests done later on a different model of "solar-dam", it was observed to be easy to operate within differences of temperatures of the order of $\Delta T$ = 60ºC on any average day of sun. So, considering an ambient temperature of 25ºC = 298 K, the maximum possible efficiency for this machine would be 20%, in those circumstances, which may be seen as an interesting number.

## 6. More recent "solar-dam" design

Further work on these ideas has led to a much simpler "solar-dam" device, letting us suspect that perhaps it would make sense to build a prototype in order to test its behaviour and efficiency. The simplification achieved allowed us to eliminate most of the components of the previous solution and reduce it to a device composed by two recipients connected by a single tube, into which pressure is supplied by independent solar panels, as shown in figure 6.

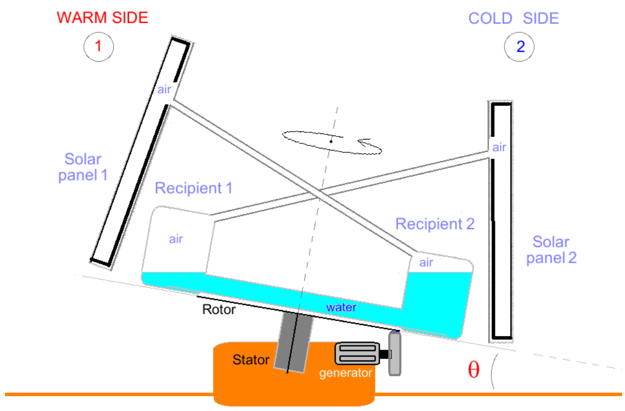


**Fig. 6** The simplest "solar-dam" model, from 2009, showing properties of both a solar and a gravitation engine.

Obviously, when the pressure from the panels moves enough water to the opposite reservoir, the system makes a turn of 180º and the process restarts. Notice that, at any instant, both the *warming effect* and the *cooling affect* contribute to moving the water into the same side of the machine. The changing on the *center of mass* is, therefore, very effective, allowing the system to easily start oscillating. In this, the machine is a gravitation engine, since gravity is used to rotate it. The pressure forcing the center of mass into movement comes from sunlight (thus it is a solar engine) but can also be supplied by anything that introduces a difference of temperature between the two sides. Notice also that the optimum condition of operation can be adjusted by simply adjusting the angle *θ*.

## 7. Some solutions and conclusions

As we now may understand, a large number of devices can be created based on this principle. The ones presented in the following figures are only some conceptual examples of what can be made. In figure 9, however, a very rustic model made of plastic water bottles is shown, with its four recipients mounted in a cross, instead of two. The dimensions of these systems can, obviously vary, from some centimetres to the height of a building. Since they are very light engines, it would be ironically funny to build one of the dimensions of a real water dam. We would be delighted to participate in such a project, if anyone would decide to finance it.

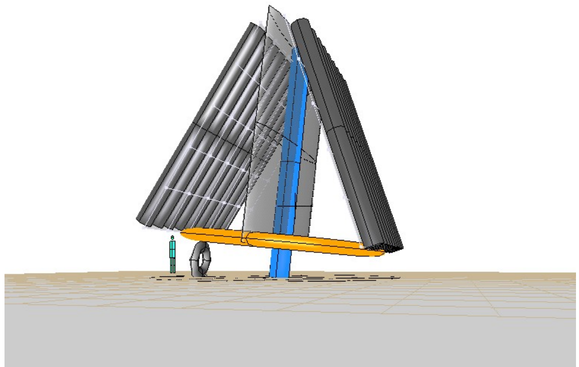

**Fig. 7** Concept of a "solar-dam" of around 7,5m high and 25m$^2$ of exposed area (~25KW of sunlight). The wheel on the ground represents the electric generator.

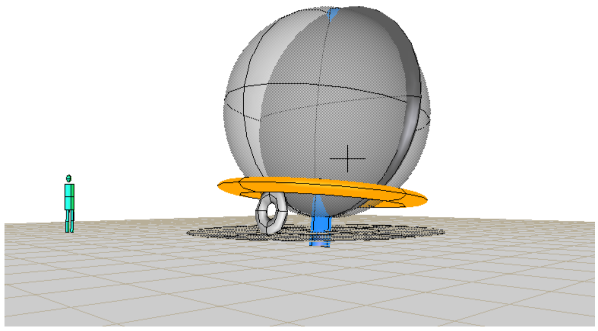

**Fig. 8** A "solar-dam" oscillating sphere (~20KW).

**Fig. 9** A rustic "solar-dam" experiment, which worked.

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# Deducing Kepler and Newton from Avicenna (ابن سينا), Huygens and Descartes

Impetus (momentum), Centrifugal force, Analytic geometry.

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7 April 2010

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KEYWORDS: classical mechanics, gravitation, universal time, center of mass, centripetal and centrifugal forces, universal constant, momentum and angular momentum.

**ABSTRACT**

With the advent of Einstein's Theory of Relativity and Quantum Mechanics, the interest in Classical Mechanics, as a field of research and philosophy, has naturally declined and almost vanished, being now practically reduced to its didactic relevance and a powerful tool for engineering. However, a fascination for the primordial questions of Physics has compelled me as a justification for once again looking at those principles regulating the movement of bodies, and to deduce from them the laws of gravitation and celestial dynamics. This time, however, this was done without the help from either Kepler or Newton. In effect, one may even say that Newton and Kepler are derived from the conceptual and mathematical manipulations presented herein, based on very simple and universal truths, some of them which have been perceived since at least the time of Avicenna[1]. Then, both the deduced gravitational force and the laws governing the planets will be compared with Newton's gravity and Kepler's laws. Finally, some considerations are drawn about Newton's gravitational constant $G$ and proposed an orbital constant $G_0$ and a gravitation force dependent on $1/r^3$.

[1] Of Persian origin, and perhaps the most notable universal thinker of the so-called “Islamic Renascence”. He was born near 1000 AD.

## 1. Introduction

What is *Gravity*?, what is *Time*?, what in reality is a *Force;* does it exist? Has anyone answered these questions? In fact not. In truth, however, we still are able to make surprising and accurate calculations based on what we perceive of all this, even without answering those questions. It is normally the *logos* that we understand, and not properly the origin of the movements. *I know who I am but I do not know where I am coming from, neither where I go to*. It is perhaps this strange conscience of a reality, a sort of a dream suspended between two unknown abysses, that sustains our curiosity and perhaps even our pleasures and fears. Life is a plan fluctuating in the unknown, which at least we know is fluctuating.

These first thoughts serve to justify the admirable contributions of our ancestors to the knowledge we proudly exhibit today, and to argue, to a certain extent, that all of them have been right in what they believed. Knowledge is a collective heritage, and those who do not expose it under such a perspective are not contributing to doing justice to their past. Avicenna, for example, nearly 700 years before Galileo Galilei, not only had already recognized the extreme importance of the product of *mass* times *velocity* (*momentum*) and called it *impetus*, but also had exposed the notion that masses would move ad infinitum due to such an *inclination* if there would be no force opposing it[2]. This ancestral perception of the causes of motion will also be used in this text as a fundamental idea,

[2] A. Sayili (1987), "Ibn Sīnā and Buridan on the Motion of the Projectile", *Annals of the New York Academy of Sciences* **500** (1), p. 477 – 482.

as we will see. Around 650 years later, Galileo and Kepler, as we know, finally launched the basis of modern science, the first with its definitive genius splitting from the remnants of an Aristotelian view of the universe, by means of its *Law of Inertia* (later called the first law of Newton), and the second with its extraordinary spirit of measuring and geometrical reasoning, which detected that planets were describing elliptical orbits around the Sun, while sweeping out equal areas during equal intervals of time, with each orbital time being a constant related to the semi-major axis of such orbits. And when Descartes develops *analytic geometry,* which made it possible to represent these geometrical forms by means of algebraic equations, and Huygens unveils his famous *centrifugal force* equation ($F_c = m.v^2/r$), all the bases have in fact been launched so that Isaac Newton could brilliantly integrate this knowledge into his three laws of mechanics and a theory of gravitation. Nevertheless, and in a certain sense, since Newton, mechanics have started to be more focused on how systems evolve in time and less on their geometrical secrets. Differential calculus becomes powerful, and through it the genius of Newton has definitely transformed the perspective of his times, turning it into a more reductionist view, contrary to the previous holistic tendency for geometrical laws and properties, which frequently were independent of time. But, is *time* really important to the dynamics of the universe, or only to the human being? Does it matter *when* something will happen, if we already know it *will* happen?

## 2. Center of mass and universal time

Thinking of Avicenna, what is the source of the "force" which moves the masses? Is there really a force, or simply an *inclination* for the movement, that can even be a spatial *inclination*, for example. Do masses feel each other? Or do they not, and what they feel is an *individual* tendency forcing them to move into a certain and *same point* in the space? Indeed, suppose there is no mass at rest, instead, all masses are being accelerated into a single point somewhere in the universe, the *center of mass of the universe* ($CM_u$). Could such a tendency be the *inclination* already perceived by Avicenna? Could it be that masses are not attracting each other but instead *falling together* into the same point, their center of mass? That way, the idea that *momentum* is exchanged between masses in order to produce a force of attraction, as certain modern theories proclaim, is not necessary. If the only and single force comes from the *total mass* concentrated in a single point (*CM*), the rest are artefacts, impressions, illusions of attraction.

Let us start to imagine that this is true. In an imaginary system of only three masses, as depicted in figure 1, we assume that none of the masses *feels* the other two. Instead, each mass feels the "call" of a *single* and same point in the space: the center of mass (*CM*). This brings something interesting related to what we have been talking about: masses already "know" that their destiny is to be pushed into that point in the space. Whether they will reach it, or simply orbit around it, will depend only on their initial conditions of movement, or their *impetus*. Certain is, however, that each of the masses will only feel completely at rest (free of tension) when it will share such a special point, either physically or geometrically.

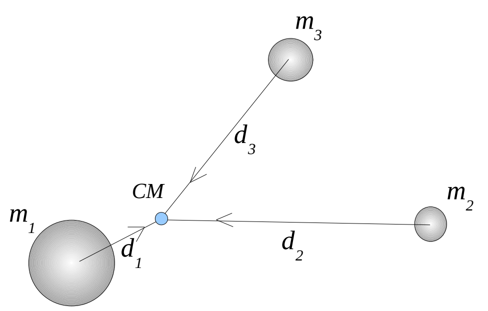


**Fig. 1** Three masses falling into the center of mass (*CM*).

Another important aspect is related to *time*: any solution must imply that all the masses will spend the same amount of time[3] on reaching the CM, as they naturally will meet there in a single *event*. Since we know this *event* is "marked" to happen in the future, each mass must spend precisely the *same time* travelling into it. *Time* may, therefore, be seen as an almost irrelevant parameter, something that simply tells us how *fast* or *slow* the process will occur, but nothing special beyond that. *Time* can be seen, in this perspective, as a simple parameter with which humans express geometric laws of nature in

[3] notice that we are considering *free fall*, therefor the initial velocity is null.

terms of parametric equations. Here we may call this the *universal time* ($t_u$).

Thus, since $t_u$ is a constant from the perspective of each mass, we may say that $t_1 = t_2 = t_3 = t_u$. Or, which is the same, that $t_u$ will be a constant of the system. It can also be written, however as:

$$t_u = d_1/v_1 = d_2/v_2 = d_3/v_3 = constant \qquad (1)$$

It is this *constant* that simply tells us whether what is to happen will be fast or slow, but nothing about what is to happen. Notice that the previous expression will be valid for any instant of time, therefore we may write, for any of the masses:

$$\boxed{d_{(t)}/v_{(t)} = constant} \qquad (2)$$

That is, as we can see, motion will be ruled by the geometric parameters and tendencies expressed by $d_{(t)}$ and $v_{(t)}$. And velocity may be seen as the tendency of the changing of a geometry in relation to the *universal time*. The *universal time*, being a constant, will be almost irrelevant. As an example: the flower is contained in the seed of the plant. What does velocity of the development of the plant mean? What if systems always move as a whole?

## 3. Generalizing the conservation of momentum

Thinking still on the *impetus* of Avicenna, as well as on the *Law of Inertia* of Galileo Galilei, we feel impelled to look at the conservation of *momentum* ($m.v$) as being a particular case of a more general principle: the principle of *conservation of angular momentum* ($r \times m.v$). In fact, if we consider any observer to be represented as a single point (the origin of a coordinate system), then, in truth, there are only angular motions in relation to that point, except in the very particular cases of when the movement is made along a straight line containing such a point. Only in this case is the motion rectilinear relative to the observer, like in the case of the *free fall*, for example. As the next figure suggests, any other "rectilinear" motion can be seen as angular. From this we conclude that we should mostly use the principle of *conservation of angular momentum*.

By figure 1, which represents a general case of rectilinear motion in relation to the observer *obs*, it is easy to see that the distance from *obs* to the body of mass *m* (moving with constant velocity vector $\underline{v}$) is dependent on the position $\underline{r}$ of the object. Such a distance can be represented as something like a conic figure[4], a hyperbole in this case. So, with the same basic mathematical expression of the ellipse and the parabola, which are figures typically related to planetary motion. Thanks, René Descartes.

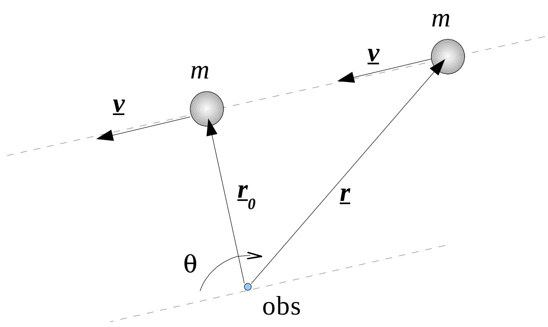


**Fig. 2** Rectilinear motion as a form of an angular motion.

Notice that the observer really *sees* the body approaching him/her till the minimum distance of $\underline{r}_0$, and then going away again, as the angle $\theta$ goes form 180º to 0º. This angle is, of course, the angle between $\underline{r}$ and $\underline{v}$ at the instant of time. So, it is as if the body would be moving along a curve, as it does in the space-time diagram (Fig. 3), and not along a straight line.

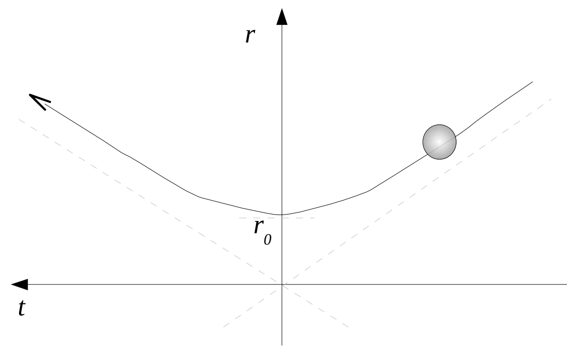


**Fig. 3** Space-time diagram of a rectilinear "angular" motion. Notice that the parabola inclination depends on the *velocity*.

Curiously, the body is still maintaining constant its angular momentum $\underline{L}$, which is given by:

$$\underline{L} = \underline{r} \times m.\underline{v} \qquad (3)$$

[4] Ellipse, parabola, hyperbole: $ax^2 + bxy + cy^2 + dx + ey = f$

$\underline{L} = r \,.\, m.v \,.\, sin\theta \;\; \underline{u}_L$
$$\underline{L} = m \,.\, r.v.sin\theta \;\; \underline{u}_L \qquad (4)$$

Where $\underline{u}_L$ represents a unitary vector (*versor*) perpendicular to the plan of motion. We thus may conclude that $r.v.sin\theta$ is a constant too.

Since we know $r.v.sin\theta$ is the *area swept per unit of time*, we may simply understand that *angular momentum* in fact means *mass* times the *rate of change of the swept area* (or <u>area speed</u>), which is a constant of the movement. *Angular momentum* is therefore a double quantity: a cinematic quantity times the "inertia" imposed by a mass.

Noticing that $v_\perp$, the component of $\underline{v}$ along the perpendicular to $\underline{r}$, is precisely given by $v.sin\theta$, as shown in figure 4, and we can then write the area swept per unit of time as:

$$dA/dt = r \,.\, v_\perp = constant \qquad (5)$$

We are, of course, deducing here that the two areas represented in figure 4 are in fact equal, and their value is constant for any instant of time.

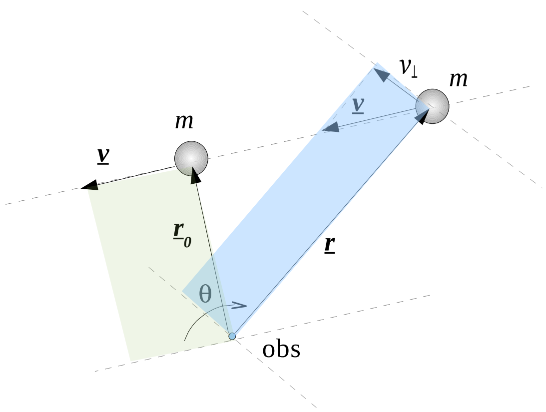


**Fig. 4** Conservation of the *area swept per unit of time*.

When Johannes Kepler discovered "his" second law[5] he was, as we see from these thoughts, simply discovering the *angular momentum* properties, or, saying better, the properties of the <u>area speed</u>. The very interesting thing here is: such a law does not only apply to planets in orbit but also to bodies moving freely and in "rectilinear" motion, under no applied forces at all. So, this law of Kepler is neither a law of the planets nor related to the gravitational field. It is a more universal law of motion which is called *conservation of angular momentum*.

But there is another interesting property of angular momentum: since it defines a *pseudo-vector* which naturally tends to avoid change, it also tends to reduce the *degrees of freedom* of the motion, by "compacting" it into a planar surface. This is intimately related to the motion of the planets, of course. And the power of such a "compaction" is obviously contained in the mass, for a given *area speed*. The power of a thing is contained in its mass, the rest are probably cinematic properties of the geometry. It is much easier to change the orbit of our Earth, for example, than if Jupiter would fly in our orbit, which has around 300 times more mass than the Earth.

## 4. Free fall in a two-body system

Based on the previous ideas, we will now start to derive an expression for the *central force* ($F_{CM}$)[6] in a two-body system. Thus, let us imagine two masses, $M$ and $m$, separated by a distance $r_M + r_m$, and let us also assume the observer is positioned at the *center of mass* (*CM*), as depicted in the figure:

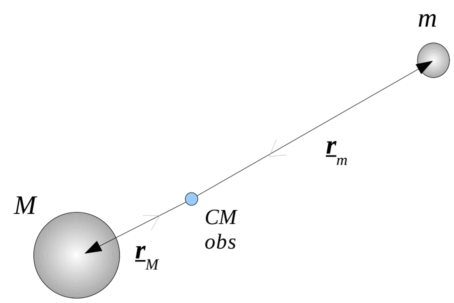


**Fig. 5** Two bodies falling into the center of mass (*CM*).

Then, we may express the position vector of the center of mass as:

$$\underline{CM} = (-\underline{r}_M \,.\, M + \underline{r}_m \,.\, m)/(M+m) = \underline{0} \qquad (6)$$

Since the vector of the center of mass in relation to an observer located at the center of mass is a <u>null</u> vector, we can write:

[5] A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.

[6] We use this term instead of centripetal force in order to better link it to the idea of a *central acceleration*.

$$(-\underline{r}_M \,.\, M)/(M+m) + (\underline{r}_m \,.\, m)/(M+m) = \underline{0}$$

or, after obvious manipulation, deduce that:

$$\boxed{M \,.\, \underline{r}_M = m \,.\, \underline{r}_m} \tag{7}$$

This is an important result, since it tells us that, for any instant of time, the system must obey this "law" of "balance" between the two masses. The *CM* is the point where these masses are in equilibrium. So, both masses naturally will tend to either "fall" into or rotate around that point. We are at the moment considering *free fall*, however; but we may conclude something more from this simple equation. If we differentiate it with respect to time, we get:

$$M \,.\, d\underline{r}_M/dt = m \,.\, d\underline{r}_m/dt$$

$$\boxed{M \,.\, \underline{v}_M = m \,.\, \underline{v}_m} \tag{8}$$

Which represents the "law" of *conservation of momentum* (*m.v*), curiously. Notice that, by this expression, the velocities of the two bodies *must* at any time be related by the *ratio of their masses*, no matter how fast the masses move; and this must hold not only for constant velocities but also in the presence of an acceleration. In this last case we may even get, by differentiating again:

$$\boxed{M \,.\, \underline{a}_M = m \,.\, \underline{a}_m} \tag{9}$$

From where we conclude that, if there is a force acting, then each mass has to feel the same force.

Finally, dividing equation 7 by equation 8, we also find the result:

$$\underline{r}_M/\underline{v}_M = \underline{r}_m/\underline{v}_m \tag{10}$$

Which is precisely the *constant* of the system we previously have named the "*universal time*" ($t_u$); the same as saying, *time is the same for every body*.

We must not forget, anyhow, that the velocities and the accelerations used herein are only those components parallel to the irrespective position vectors, so, only a part of the reality if compared with general motion and orbital systems. From now on we will distinguish them by the symbols $_{//}$ for parallel and $\perp$ for perpendicular.

## 5. Angular momentum

Let us now go a bit further and notice that for any kind of motion the two bodies will be involved in, the *total angular momentum* of the system must be a constant too. So, in relation to our observer located at the center of mass we must write that the total angular momentum is, of course, the sum of the angular momenta of the two bodies:

$$\underline{L}_{total} = \underline{r}_M \times M \,.\, \underline{v}_M + \underline{r}_m \times m \,.\, \underline{v}_m \tag{11}$$

$$\underline{L}_{total} = M \,.\, \underline{r}_M \times \underline{v}_M + m \,.\, \underline{r}_m \times \underline{v}_m$$

$$\underline{L}_{total} = (M \,.\, r_M \,.\, v_{M\perp} + m \,.\, r_m \,.\, v_{m\perp}) \,.\, \underline{u}_L \tag{12}$$

Which is an expression already using the concept of *area speed*. Since we know that $\underline{u}_L$ will also be constant, it defines the plan of the motion, we may now represent this expression in the scalar form:

$$\boxed{L_{total} = M \,.\, r_M \,.\, v_{M\perp} + m \,.\, r_m \,.\, v_{m\perp} = constant} \tag{13}$$

Figure 6 represents a general case of motion where both bodies have parallel and perpendicular velocities. Notice, though, that no external forces are considered to be applied to them, so, the parallel components of the velocities are due to their natural *attraction* into the *CM*.

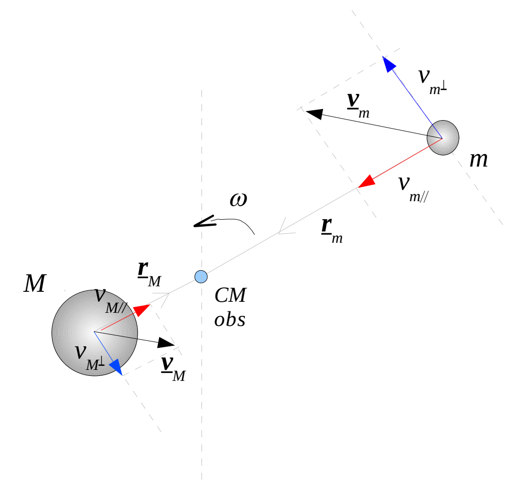


**Fig. 6** Two bodies moving around the center of mass (*CM*).

It is not difficult to see that in a system like this, in every instant both masses have to rotate with the same angular speed $\omega$, even if this speed will not be constant in the time; otherwise, the center of mass could get out from the straight line connecting the two bodies, which is mathematical nonsense. We may, therefore, by the definition of *angular speed*, write the equalities:

$$\omega_M = v_{M\perp}/r_M = \omega_m = v_{m\perp}/r_m = \boxed{\omega(t)} \qquad (14)$$

So, equation 13 can be written as:

$$L_{total} = M \,.\, \omega \,.\, r_M^{\ 2} + m \,.\, \omega \,.\, r_m^{\ 2} = const \qquad (15)$$

Now, using the expression 7 in order to let us eliminate $r_M$ from this equation, so that we may treat the problem focusing the attention more on the motion of the smaller body, we get:

$$L_{total} = M \,.\, \omega \,.\, (m/M)^2 \,.\, r_m^{\ 2} + m \,.\, \omega \,.\, r_m^{\ 2} \qquad (16)$$

$$L_{total} = \omega \,.\, r_m^{\ 2} \,.\, m \,.\, (M+m)/M \qquad (17)$$

Compressing the constant term which depends on the masses into:

$$\boxed{K_M = m \,.\, (M+m)/M} \qquad (18)$$

We get:

$$L_{total} = \omega \,.\, r_m^{\ 2} \,.\, K_M \qquad (19)$$

Notice that, for the general case, everything is a constant in this equation except possibly $\omega$ and $r_m$, which may change with time. But, in the particular case of a *circular orbit*, these two quantities are also constant. Thus, when Galileo Galilei used to argue that the perfect orbits for the planets should be circles he was in fact right. Those are the most stable orbits, although other orbits can also occur as long as the product $\omega \,.\, r_m^{\ 2}$ remains constant. Notice that this product is precisely, and once again, the *area speed*. For reasons of convenience, let us for now rewrite the previous equation as:

$$\boxed{\omega = \{ L_{total} / K_M \} / r_m^{\ 2}} \qquad (20)$$

## 6. The central force

We already know that, if there is a *central force* acting on the bodies, the force on the mass *m* is precisely the same (although in the opposite direction) as the force acting on mass *M*. We may now use Huygens testimony about the existence of a force acting on bodies when these move in a circle with radius *r* and linear speed *v*, which pull them apart from the center of the rotation. As we know, Huygens gave to it the name "*centrifugal force*", and expressed it by:

$$F_c = m \,.\, v^2 / r \qquad (21)$$

We may now look into this in different ways. We may imagine that the *centrifugal force* appears naturally every time a body is made to change its direction of motion, as a sort of *reaction* to what *forced* such a change: a *central force*; or we may think of it as an *apparent force* due to inertia, in fact non-existent, that seems to appear under the action of a *central force*. That is, however, the force needed to act on the body in order to restrain its motion into a circle, usually called *centripetal force*. For long time a discussion about this issue remains in the academic circles, as we know. Perhaps in a future article we will address such a debate, but for now it is not our intent. Let us simply pick up the second position, and think that a body needs to be acted upon by a *centripetal force* given by equation 21 in order to exhibit an angular motion. So, if the body gets angular motion, it obviously also gets *angular speed* ($\omega = v/r$), and the expression of our *centripetal force* can now be written as:

$$F_c = m \,.\, r \,.\, \omega^2 \qquad (22)$$

Using equation 20 for the *angular speed*, in the case of two bodies that we are analysing, we can deduce that the *central force* originating from the *center of mass* and acting on the smaller body is given by:

$$\boxed{F_{CM} = m \,.\, \{ L_{total} / K_M \}^2 / r_m^{\ 3}} \qquad (23)$$

This expression seems to tell us that the *central force* responsible for planetary motion, for example, is dependent on $1/r^3$, and not on $1/r^2$ as proposed by Newton. And, in a beautiful and simple way, it tells us also that the *gravitational constant*[7] of Newton probably results from two other constants of the system: the *total angular momentum* and a *relation between masses*. But this expression may even raise another question: could it be that the *universal gravitational constant* ($G$) is not really universal, but and approximation dependent on the system?

## 7. Comparing with Newton's gravitation

We will now try to compare the last results, mainly equation 23, with what is commonly known as the *Theory of Gravitation* of Newton, which equation for the gravitational force is:

$$\boxed{F_{newton} = m \,.\, M \,.\, G \,/\, r^2} \qquad (24)$$

Notice, however, that this expression uses the distance between the two bodies, which is given by $r = r_M + r_m$, while our expression uses the distance of the mass $m$ to the $CM$. We must, therefore, rewrite it properly. Considering equation 7, we can write:

$$r = r_M + r_m = (m/M)r_m + r_m = r_m \,.\, (m/M + 1)$$

$$r = r_m \,.\, (M+m)/M$$

But, since from equation 18 we have:

$$K_M = m \,.\, (M+m)/M$$

we can write:

$$r = r_m \,.\, K_M \,/ m \qquad (25)$$

Newton's force may now be arranged to become:

$$F_{newton} = m \,.\, \boxed{M \,.\, G \,.\, \{\, m \,/\, K_M \,\}^2} \,/\, r_m{}^2 \qquad (26)$$

Which can finally be compared to the expression previously derived for the *central force* (equation 23), written below in a more appropriate form and called $F_{feliz}$.

$$F_{feliz} = m \,.\, \boxed{\{\, L_{total} \,/\, K_M \,\}^2 \,.\, (1/r_m)} \,/\, r_m{}^2 \qquad (27)$$

[7] $G = 6.67428 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

For the two forces to be equal, it must hold:

$$M \,.\, G \,.\, \{\, m \,/\, K_M \,\}^2 = \{\, L_{total} \,/\, K_M \,\}^2 \,.\, (1/r_m)$$

$$\boxed{G = L_{total}{}^2 \,/\, \{\, M \,.\, m^2 \,.\, r_m \,\}} \qquad (28)$$

This result is somehow surprising because we were expecting to find $G$ as a constant. On the contrary, $G$ appears here dependent on $r_m$. This way, it would only be a constant in those particular cases of circular orbits, or near, where $r_m$ can be seen as a constant too. Anyway, testing this relation by means of *dimensional analysis* results in a truth, meaning that, somehow, Newton has included a distance into his universal constant. It is time, therefore, for us to inspect the way Newton had deduced his *Law of Gravitation*.

## 8. Newton's deduction of gravitation

The idea of Newton was, somehow, very simple, although probably genial for his times, when a structured knowledge of Physics and mathematics were at its beginning. Newton's ability for cleaning away the fog around the subjects and transforming them into coherent systems of thought, or models, was in fact extraordinary for that time. Even so, perhaps there were some small uncertainties related to his calculations that may explain the slight divergence between $F_{newton}$ and $F_{feliz}$.

It seems[8] Newton has started by considering that the force acting on a body describing a circle or ellipse had to be of the same order asthe centrifugal force discovered by Huygens. Only that way the body would be able to maintain its closed loop trajectory. Thus, Newton considers a *gravitational central force* ($F_g$) coming from a single point, and starts with the equation:

$$F_g = F_c = m \,.\, v^2 \,/\, r \qquad (29)$$

Then, deciding to use the period of the orbit ($T$) as well as the orbital path ($2\pi\, r$), he computes the orbital speed as $v = 2\pi\, r/T$ and writes:

[8] I didn't read his "*Philosophiæ Naturalis Principia Mathematic*", but only an analysis of his method, in Steffen Ducheyne, "*Mathematical Models in Newton's Principia: A New View of the "Newtonian Style"*", Centre for Logic and Philosophy of Science, Ghent University, Belgium.

$$F_g = m \,.\, \{ 2\pi \,.\, r / T \}^2 / r \quad (30)$$

$$F_g = m \,.\, 4\pi^2 \,.\, \{ r^2 / T^2 \} / r$$

As we can see, there are already some questions here. Why compute an *average speed* by means of an *average time* ($T$) and an *average radius* ($r$) and use them in what should be an *instantaneous* equation? This seems to result from a strategy of adapting his formula to what he already knew empirically from Kepler. Newton, in fact, obviously does it when he decides to multiply this equation by $r/r$, that way achieving the form:

$$F_g = m \,.\, \boxed{4\pi^2 \,.\, \{ r^3 / T^2 \}} / r^2 \quad (31)$$

Since he knows from Kepler that $r^3 / T^2 = const$, he can finally deduce that the *central forces* responsible for planetary motion are of the $1/r^2$ type. From here to the more general equation known today it is only a small step, if one imposes the presence of the mass $M$, and, by dimensional manipulation, discovers the constant $G$. That is, if we say that:

$$4\pi^2 \,.\, \{ r^3 / T^2 \} = M \,.\, G \quad (32)$$

We finally arrive to the well-known equation of Newton's gravitation:

$$\boxed{F_g = m \,.\, M \,.\, G / r^2} \quad (33)$$

## 9. $G_{newton}$ versus $G_{feliz}$

Kepler's more exact expression for the third law must take into account the two masses involved, that is (M+m) in place of M, in equation 32. Then, it can be written in a simpler form if we use the concept of angular speed $\omega = 2\pi / T$. That is:

$$\omega^2 = G \,.\, (M+m) / r^3 \quad 34)$$

We must, however, remember that this equation was derived based on *average quantities*, therefore it should, in a more realistic way, be written as:

$$\omega_{avr}^{\ 2} = G \,.\, (M+m) / r_{avr}^{\ 3} \quad (35)$$

Since we have, from the ellipse geometry:

$$r_{avr} = (r_{min} + r_{max}) / 2 = a$$

where $a$ represents the ellipse *major semi-axis*, we finally can write an equation representing what was really observed by Kepler in his experiments:

$$\boxed{\omega_{avr}^{\ 2} = G \,.\, (M+m) / a^3} \quad (36)$$

It is now easier to have a better idea of what Newton's *universal constant* $G$ means. By properly arranging this equation we get:

$$\boxed{G_{newton} = \omega_{avr}^{\ 2} \,.\, a^3 / (M+m)} \quad (37)$$

Which obviously shows that $G_{newton}$ represents an average quantity. This must now be compared with the expression for $G$ derived by our method, that is, with equation 28, which we reproduce here as:

$$G_{feliz} = L_{total}^{\ 2} / \{ M \,.\, m^2 \,.\, r_m \}$$

Knowing, that $L_{total} = \omega \,.\, r_m^2 \,.\, K_M$, as deduced in equation 19, this expression can be written:

$$G_{feliz} = \omega^2 \,.\, r_m^{\ 4} \,.\, K_M^{\ 2} / \{ M \,.\, m^2 \,.\, r_m \} \quad (38)$$

We now need, first of all, to transform $r_m$ into $r$, in order that the two approaches can be compared, which can easily be done using equation 25 again, that is $r = r_m \,.\, K_M/m$, and transforming the previous relation, with a bit of manipulation, into:

$$G_{feliz} = \{ \omega^2 \,.\, r^3 / M \} \,.\, ( m/K_M ) \quad (39)$$

Since we know that $K_M = m \,.\, (M+m)/M$, we can deduce that:

$$\boxed{G_{feliz} = \omega^2 \,.\, r^3 / (M+m)} \quad (40)$$

From all this, of course, results:

$$\{ G_{feliz} / G_{newton} \} = \{\omega / \omega_{avr}\}^2 \,.\, \{r/a\}^3$$

which shows that the two quantities are equal only in the case of circular orbits, not in general. And, if we look again into equation 36 arranged in the form:

$$\omega_{avr}^{\ 2} \cdot a^3 = G \cdot (M+m) = constant \qquad (41)$$

these thoughts also lead us to try to better understand what Kepler's observations mean, since we know that <u>*area speed*</u> (let us called it $K_A$), which is given by the product $\omega \cdot r^2$, is also a constant of motion for each orbit. On one side, we know from Kepler that dimensionally $[\omega^2 \cdot r^3]$ is a constant of motion; on the other, *area speed* squared is also a constant of motion:

$$\boxed{\omega^2 \cdot r^4 = K_A^{\ 2} = constant} \qquad (42)$$

If we call them $C_K$ and $C_0$, for example, we have:

$$C_0 = \mathrm{r} \cdot C_K$$

which makes us think that the two constants may perhaps be a single one, which is dependent on $r$:

$$C_K = C_K(\mathrm{r}) = C_0 / \mathrm{r} \qquad (43)$$

This means that the Kepler constant is in effect a universal constant, but can be seen as an *area speed squared* (energy per unit mass?) losing strength as it gets away from the *center of force*, precisely at the same pace of the energy density: $1/r$.

## 10. An orbital constant $G_0$ and $1/r^3$ forces?

Keeping in mind that the total *area speed* ($K_A$) is in fact a *constant of motion* for each orbit, we can again use the expression previously deduced for the force "pushing" masses into the *CM* (equation 27):

$$F_{feliz} = m \cdot \{ L_{total} / K_M \}^2 \cdot (1/r_m) / r_m^{\ 2}$$

$$F_{feliz} = m \cdot \{ L_{total} / K_M \}^2 / r_m^{\ 3} \qquad (44)$$

Since $L_{total} = \omega \cdot r_m^{\ 2} \cdot K_M$, we may write it again in the form:

$$F_{feliz} = m \cdot \{ \omega \cdot r_m^{\ 2} \cdot K_M / K_M \}^2 / r_m^{\ 3}$$

$$F_{feliz} = m \cdot \{ \omega \cdot r_m^{\ 2} \}^2 / r_m^{\ 3} \qquad (45)$$

Expressing $r_m$ in terms of $r$, since we know it holds $r = r_m \cdot K_M/m$, and considering $K_A = \omega \cdot r^2$, we will find:

$$F_{feliz} = m \cdot K_A^{\ 2} \cdot (m/K_M) / r^3 \qquad (46)$$

Once again using $K_M = m \cdot (M+m)/M$, we get:

$$F_{feliz} = m \cdot K_A^{\ 2} \cdot \{ M/(M+m) \} / r^3 \qquad (47)$$

And so, rearranging:

$$F_{feliz} = m \cdot M \cdot \{ K_A^{\ 2} / (M+m) \} / r^3 \qquad (48)$$

If now we start to use as an <u>*orbital constant*</u> the quantity defined by:

$$\boxed{G_0 = K_A^{\ 2} / (M+m)} \qquad (49)$$

We finally deduce the new equation for the gravitational field, which we expect to be valid under any circumstances, as:

$$\boxed{F_{feliz} = m \cdot M \cdot G_0 / r^3} \qquad (50)$$

Two aspects fast emerging from this expression appear of interest: first, the fact that $G_0$ will be a true constant[9] of the *orbital motion* in question, obviously related to the conservation of angular momentum; second, the $1/r^3$ dependency makes us think on what could perhaps be a curious similarity between gravitation and magnetism.

## 11. Some aspects and conclusions

With a bit of manipulation of equations 41 and 49 we can deduce that $\underline{G_0 \simeq G \cdot a}$. So, the previous equation can be written as:

$$F_{feliz} = m \cdot M \cdot G \cdot a / r^3$$

$$F_{feliz} = \{a/r\} \cdot \boxed{m \cdot M \cdot G / r^2} \qquad (51)$$

$$\boxed{F_{feliz} = \{a/r\} \cdot F_{newton}} \qquad (52)$$

from where we can deduce that $F_{feliz}$ contains in

[9] Notice that $G_0$ can be easily computed by squaring the product of *distance* times the *speed* at either the *Perihelium or* the *Aphelium,* and dividing it by the *total mass*.

itself the term $\{a/r\}$ which is usually treated as a perturbation to the Newton's equation. We expect, therefore, that $F_{feliz}$ automatically corrects $F_{newton}$. Notice that Newton was linking this term to the following relation of masses:

$$\{a/r\}^3 = M / (M+m) \tag{53}$$

**Author's Biography:**

J. Manuel Feliz-Teixeira graduated in Physics in the Faculty of Sciences of the University of Porto, and holds an MSc and a PhD from the Faculty of Engineering of the same university. His PhD thesis is on "*Flexible Supply Chain Simulation*". Lately he is also dedicated to researching new approaches for renewable energy, as well as interested in Classical Mechanics specially related to *gravity* and *anti-gravity* phenomena.

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# Almost a Flying Saucer

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**ABSTRACT**

One of the most fascinating subjects on our way to the understanding of the laws of the Universe is the almost delirious search for the ability to levitate (ourselves and objects), which in modern times also became associated with some *anti-gravity* purported effects, fantastic space ships, as well as with what is commonly known as *flying saucers*. A significant number of proposals for achieving such abilities claimed as *anti-gravity* are focused on the *gyroscopic effect* observed when a fly wheel is suddenly forced to move out of its initial plane of rotation [1]. The law of Physics for the conservation of angular momentum results here in the appearance of what some explain as 'apparent' forces, which give the observer the illusion that it is close to achieving the goal of building an *anti-gravity* device. This article deals with some of the thoughts usually behind such claims, proposals and experiments, and has the intention of contributing to a better understanding of the mechanical effects involved in these gyroscope based devices.

## 1. Introduction

A simple search on the Internet will result in thousands of documents found about *anti-gravity*. Among articles of opinion, purported discoveries, claims of new devices and even the promotion of personalities (as well as conspiracy theories, some probably true, some not), there is however something we consider an extraordinary symptom: finally the possibility of researching, discussing, producing experiments and publication of ideas is spreading globally, and being made available to people in general. Even if not all those people are able to manipulate the mathematics of the phenomena, at least some of them do and many of them reveal very interesting levels of intuition and imagination. It is, in our opinion, the beginning of the liberation of the creative mind from the old *schools of thought*, since, at a certain level, those schools frequently act more as an obstruction to new ideas than to bring them to light. There is, however, in this apparently chaotic system named the Internet, a large amount of information which is fake, exaggerated, incorrect, or simply deliberately wrong or destructive, therefore not deserving credibility. In a certain sense that is also understandable, since even in schools and research institutions it is sometimes difficult not to question credibility, mainly when it comes to a subject where logic is still surrounded by the cloud of fantasy and imagination. It is not surprising, therefore, that some sort of hallucination will emerge and even affect people in such a space when touching on such matters. Adding to this a certain love affair with illusionism frequently found in certain minds, we may definitely state that hallucination is going global in the Internet. And the subject of *anti-gravity* is of the most preferred ones, due, of course, to the fact it is on the edge of current knowledge; it is associated with the fascinating stories of flying saucers of the 60s; it deals with the unknown, etc. Although we are also human, we will try to be as wise as possible in commenting about this matter in the next sections. This article is as an introductory text about the idea of building an *anti-gravity* craft.

## 2. What is *anti-gravity*?

In effect no one knows what *gravity* is, so, anyone who will talk about *anti-gravity* can only be talking in an abstract sense. What certain people already know and understand is the *effect of gravity*: a strange *acceleration* which is produced in objects at a distance and resembles an attraction field coming from who knows where. That is, we are currently able to measure gravity, but we don't yet know where it is coming from, its origins. Contrary to what happens with the electromagnetic field, which we already know is a result from the movement of charged particles, both *gravity* and *magnetism* are still a mystery for the physicists.

The term *anti-gravity* is also frequently used in an abusive way, since certain people mention it even when other type of phenomena are used to suspend objects above the ground, like jet propulsion, fluid lift effects (*Coandă effect*, etc.), repulsion of magnets, electronic repulsion effects, and so on... So, before knowing what *anti-gravity* is it is important to recognise what *anti-gravity* definitely is not.

Since the gravity effect is a *vectorial* quantity, an acceleration, it seem to us reasonable to expect an anti-gravity device to be based on some kind of vectorial principle or phenomenon, and not on a simple transfer of power (energy) which in effect represents a *scalar* quantity. This means that we are at least convinced that anti-gravity may only be achieved by creating a *vectorial* field that can be made opposite to the field of gravity, therefore it must come from some *vectorial* principle. Could magnetism, for example, play an effective role on creating such effect? The discussion could be extended, but it is not the subject of this article. What is important here is to recognise that since long ago people were curiously looking at the *gyroscopic effect* as an excellent candidate for letting us achieve anti-gravity, a *deus-ex-machina* concept which frequently we suspect mankind is not yet prepared for. Even so, the bet seems to follow a good path: the *gyroscopic effect* is a *vectorial* effect and not a *scalar* one. It is not derived from the *principle of conservation of energy*, but from another extremely important principle of Physics: the *principle of conservation of angular momentum*. This is very interesting because *high momenta* are associated with the rotation of *high masses*, what seems a little compliment to the notion "*the heavier the lighter*", as we imagine it to be true in a real *anti-gravity* phenomenon. We hope such a discussion will be addressed in future articles; at this point, however, we will focus the attention on what is commonly called the *gyroscopic effect*.

## 3. The *gyroscopic effect*

This is the effect responsible for maintaining the equilibrium of the toy called *top*, or *spinning top,* while it spins. It is, therefore, an effect produced by rotation, which tends to react against the expectable effect of the gravity in order to maintain the system rotating in its initial axis of rotation. It could also be imagined as a sort of syndrome: *I am rotating around this axis, please do not disturb because I will react if you do*. In true, the effect is not even dependent on gravity, it is simply against change, a pure conservation of momentum, but the *top* spinning under gravity is an excellent example to explain and understand it.

The *conservation of angular momentum*, which in truth is a particular case of the more general *principle of conservation of momentum*, may be stated as follows: *a system will react in a way that it will conserve its angular momentum*. From this, we may already expect that a *reaction* will occur if we try to *force* the system into a different situation of *angular momentum*. Let us now inspect the *spinning top* represented in the next figure and try to understand why it does not fall while rotating:

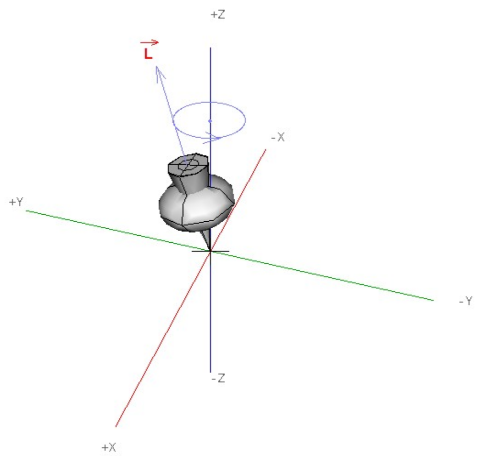


**Fig. 1** Spinning top basic movements: *spin* and *precession*.

The top spins around its axis of symmetry, and this instantaneously creates an *angular momentum* denoted by the vector $\boldsymbol{L}$ on figure 1. $\boldsymbol{L} = I\,\boldsymbol{\omega}$, where $I$ is the distribution of *mass* seen by the axis of rotation, and called *moment of inertia*, and $\boldsymbol{\omega}$ is the angular velocity. On this system, the forces of gravity are also applied, which tend to pull the top down into the *-Z* direction. Since the total $\boldsymbol{L}$ must be conserved, the spinning top reacts by producing a torque around its fixed point (origin of coordinates) in order to try to "elevate back" its mass. This torque then induces a movement of *precession* around the axis defined by the lines of force of the gravitational field (same as *Z* axis). This is known as the *gyroscopic effect*. The angular speed of *precession* is a measure of the intensity of the gravity. In the absence of gravity, *precession* would not exist, since it wouldn't be needed for anything. So, instead of falling, the top answers with a movement perpendicular to the direction of falling, as if trying to get away from that perturbation in order to avoid it. But, as the perturbation also persecutes it, the top repeats this behaviour, therefore resulting in drawing an orbit around the perturbation axis. The idea seems to be: "*in order to avoid being captured, I run away into an orbit around that which wants to capture me*".

But there are other interesting conclusions one can get from this example; for instance, one may notice that the "force" "generated" to conserve the angular momentum is of the same order of the force of the perturbation. So, the bigger the mass of the spinning top the bigger this "force". It is therefore amazing to realize that by simply spinning a mass of 1000 Kg, for example, one is able to generate "forces" of the order of 1000 Kgf, which react "against" gravity. In effect, this phenomenon can turn out to be something huge.

To better understand why some people went on to believe they had discovered *anti-gravity* based on this effect, let us exchange the *spinning top* for a horizontal *spinning wheel* mounted onto a vertical axis, as represented in figure 2. The wheel of mass *M* spins around its symmetry axis with an angular speed $\boldsymbol{\omega}_0$, thus producing an angular momentum $\boldsymbol{L}_0$. Since the wheel is rigidly connected to the central axis (*Z*) we assume that nothing will happen, as the action of the gravity will be perfectly compensated by the reaction of the structural forces suspending the arm of the wheel. That is, in this case there will be no *precession*, since nothing is trying to change the $\boldsymbol{L}_0$ vector.

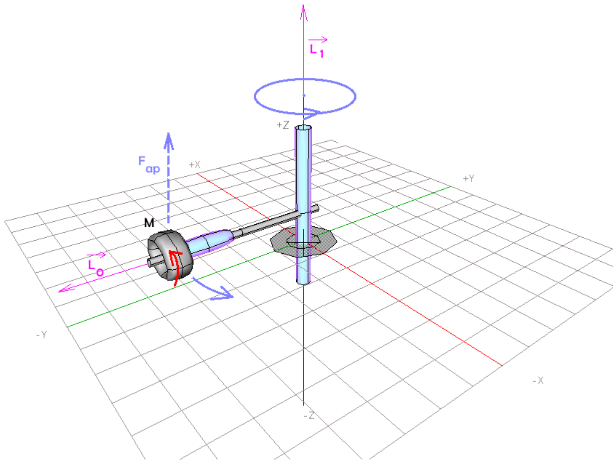


**Fig. 2** A spinning wheel's *spin* and *forced precession*.

The interesting question now is: what about if we decide to *induce* (or *force) precession* into the system? Or, in other words, what will happen if we force the system to rotate around the *Z* axis, and introduce a new angular momentum $\boldsymbol{L}_1$? Not so surprising, an *apparent force* $\boldsymbol{F}_{ap}$ trying to pull up the wheel will be generated, giving the impression of a lift. This is really a strong effect, that anyone can experiment by means of a spinning bicycle wheel, for example, arranged as suggested in the figure. This apparent force $\boldsymbol{F}_{ap}$ is even proportional to both $\boldsymbol{\omega}_0$ and $\boldsymbol{\omega}_1$; thus one could control its strength very easily. And even more: inverting the direction of the rotation around *Z*, one can invert the direction of the apparent force, purportedly making the system heavier.

If we now use several of these rotating wheels connected to the central axis, it is not so difficult to imagine a heavy spacecraft being suspended in the air by this effect, a true *anti-gravitational* effect, and to use the same effect as a method of propulsion. Some of our ancestors of the 20th century have, indeed, observed this behaviour and even followed the same direction of our thoughts. It happened principally after Word War II with the suspicion that German scientists and military forces were already in control of *anti-gravity* devices, which usually resembled a saucer. Soon this belief became popular under the term "*flying-saucer*". One can find a lot of information about this on the Internet, as we said, but, in our opinion, it is the book "*The Truth About*

*The Wunderwaffe*" (2003), from Igor Witkowsky[1], a well-known Polish journalist specialist in military technology, that may be considered the most detailed and recent historical work about the subject. Here, however, we are mainly interested in the physics of the phenomenon, therefore let us present our own proposal for a personal anti-gravity craft:

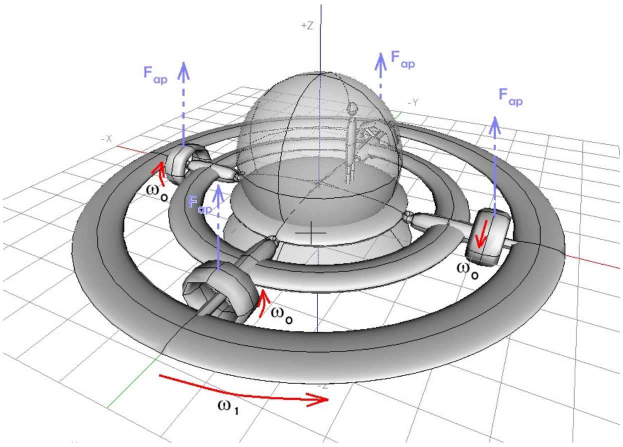


**Fig. 3** A purported anti-gravity craft with four engines driving four heavy spinning wheels, which in turn rotate around a fixed cabinet (our design).

As expected from the previous considerations, each wheel, spinning with angular speed $\boldsymbol{\omega_0}$, would be responsible for generating an apparent force $\boldsymbol{F_{ap}}$ when the circles of the machine would be made to rotate with angular speed $\boldsymbol{\omega_1}$. The overall result would be the summation of all these apparent forces, which would not only simply suspend the craft in the air but also push it up in the opposite direction of the gravity. Manoeuvreing the machine would also be an exceptional experience, since lots of possibilities could be achieved by simply changing each $\boldsymbol{\omega_0}$ and introducing variations on $\boldsymbol{\omega_1}$. The craft would be able to change direction fast, spin, quiet levitate, slowly or quickly change altitude, move horizontally or vertically, fall down like a rock, etc., as it happens in a true *flying-saucer* of our imagination.

## 4. Why don't we drive such a craft yet?

To answer this question we would like to basically suggest two main reasons: first, there was in fact a subtle but dramatic mistake in interpreting the type and direction of the *apparent forces* generated by the *gyroscope effect*. This fact invalidates the possibility of building such a craft. Second, perhaps we are not yet prepared to have such an exceptional system of transportation, since we are still too rude, insisting on developing technology based on "brute force", obviously associated with explosion, noise, chemical transformation, destructive physics; instead of on a technology of delicate interchange with the subtlety of the laws of a vectorial nature. But a third point can also be mentioned: can we really imagine regular people of today having the possibility of buying such a type of "car", something that would project actual two-dimensional human beings into the free usage of three-dimensional space? Knowing how hard it is now to receive so many messages of SPAM in our email accounts, some of them obviously futile and even insulting, please try to extrapolate it to the possibility of anyone driving a "car" above ground to wherever he or she wants, at the time he or she wants, etc. How nasty it would be to wake up relaxed in your home on the fifth floor of a building and to suddenly look out the window and see one of those abusive beings from some enterprise smiling and asking you: "*have you ever thought on creating a new Internet account with us?*". Without a real change in our way of thinking, in our mindset, anti-gravity could easily lead to an unbearable nightmare.

## 5. The true forces of the *gyroscopic effect*

It is obviously time to give an explanation about what in truth happens in the *gyroscopic effect*. We will do it now. If there is no force $\boldsymbol{F_{ap}}$ produced by the spinning wheel of figure 2, what creates such an impression? The next figure (Fig. 4) will almost by itself answer this question. The fact is, as long as we force the system to rotate around the Z axis, two forces, instead of one, appear in the spinning wheel in order to try to compensate our action: a force $\boldsymbol{F_{int}}$ in the upper part of the wheel, and a force $\boldsymbol{F_{ext}}$ in the bottom part of the wheel. These forces have opposite directions and they are always perpendicular to the *Z* axis, that is, the axis of the imposed rotation. $\boldsymbol{F_{int}}$ tries to pull the wheel closer to the *Z* axis, while $\boldsymbol{F_{ext}}$ tries to push it away from it. Notice that these forces will be inverted if we invert the direction of the forced rotation. The demoralising truth is: they are absolutely perpendicular to the *Z* axis, therefore their

[1] http://en.wikipedia.org/wiki/Igor_Witkowski

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component on this axis is null. This means, no component of acceleration is introduced along the field of gravity, so, no *anti-gravity* effect. We have been so near, and yet so far from reach.

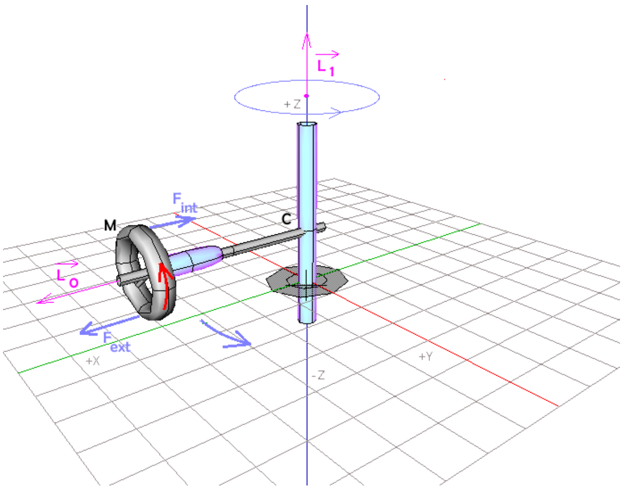


**Fig. 4** The true effect happening in a gyroscope device.

This phenomenon turns out to be due to a torque, not to a single force. Thus, the reaction to our action will be a *rotation*, not an *elevation*. To satisfy the *principle of conservation of angular momentum*, the wheel will try to rotate around the axis defined by our induced movement, but, since it is not allowed to do it because it is rigidly connect to its axis, such a rotation will propagate to the next point that is able to sustain a rotation, that is, the point denoted by "*C*" in figure 4. And this, of course, will give us the impression of an elevation of the wheel.

## 6. Why does it happen like this?

Till now we have talked about principles, but, what is it the real thing behind such behaviour? Are these forces coming from a vacuum? The truth is, they are simply an expression of *inertia*, that is, of the tendency of a mass to "avoid" being "disturbed" from its most relaxed path of movement: the *straight line*. So, in a certain way these forces represent a *complaint*. They are a kind of expression of "pain" exhibited by the mass, if allowed the abuse of such a comparison. Could force fields ultimately be seen as expressions contrary to joy? Could the universe, and even life as we sense it, result from this *pain* extended to the dimension of the universe?... where only *light* seems to be free... We don't know, but the fact is these forces appear because we *forced* the system to change its state. Figure 5 will help to explain it in detail.

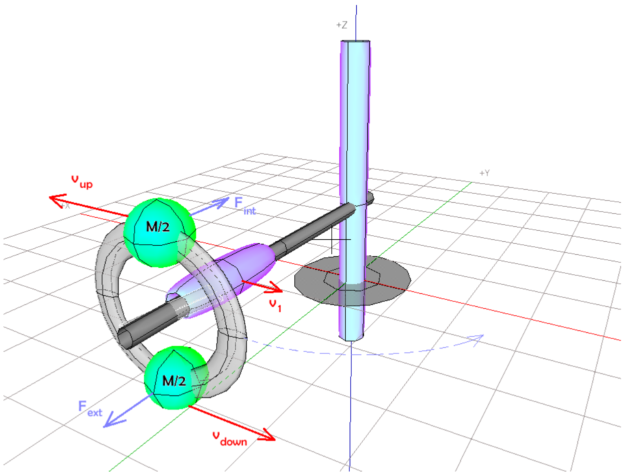


**Fig. 5** Linear velocity and torque, equivalent system.

In this figure we present an imaginary system with two spherical masses concentrated at opposite points of the wheel, and the wheel with null weight. Assuming this to be equivalent to the previous system, let us focus the attention on the linear velocities of these masses.

When no forced rotation is applied, each mass rotates with linear velocity $\boldsymbol{v_0} = \boldsymbol{r_0}\ \boldsymbol{\omega_0}$, where $\boldsymbol{r_0}$ is the wheel radius. So, in the instant where the wheel is at the position shown in the figure, $\boldsymbol{v_{up}} = \boldsymbol{v_{down}} = \boldsymbol{v_0}$.

To the contrary, when we force the system to rotate around the *Z* axis with velocity $\boldsymbol{v_1} = \boldsymbol{r_1}\ \boldsymbol{\omega_1}$, being $\boldsymbol{r_1}$ the distance from this axis to the wheel, $\boldsymbol{v_{up}}$ and $\boldsymbol{v_{down}}$ becomes obviously different, that is:

$$\boldsymbol{v_{up}} = \boldsymbol{v_0} - \boldsymbol{v_1}$$
$$\boldsymbol{v_{down}} = \boldsymbol{v_0} + \boldsymbol{v_1}$$

This means that our action has broken the previous equilibrium of the system, and exchanged the previous *symmetry* for an induced *anti-symmetry*. Its reaction starts to be completely understandable now. What happens when a mass rotating with a certain speed around an axis sees its speed increased? The answer is: that mass will feel a force pushing it away from the rotation axis in order to conserve angular momentum. And what happens when the speed of that mass decreases? It will feel a force pulling it to the rotation axis, for the same reason. In truth, what happens in our wheel is these two effects acting at the same time. The lower part is pushed away from the *Z* axis, while the upper part is pulled to the *Z* axis. The result is a torque which tries to align the angular momentum of the wheel with the external angular momentum imposed by us. And, of course, this creates an *apparent force* that levitates the wheel, but at the same time pushes down the *Z* axis.

We see that forces originate in the need to conserve momentum, and any attentive reader will for sure notice a perfect parallel between this case and what happens in magnetism, atoms, planets, etc. In a certain sense, we may even consider that we have produced *anti-gravity,* but at the same time we have produced the same "amount" of *gravity,* and the result is automatically null; also, such effects belong to the plane defined by the induced rotation, so no components can be projected onto the axis of rotation. Could it be that there is a way of breaking such an *anti-symmetry* and let the *anti-gravity* effect naturally emerge in order to be useful in practice? That seems to be the only mystery now; anyhow, we suspect the answer is yes.

## 7. Conclusions

Contrary to the illusion of the common sense which tells us the forces created by the *gyroscopic effect* could probably be used to elevate a craft against the field of gravity, we have shown that in truth this effect is due to a *pair of forces* (binary) acting at the same time in opposite directions. These forces induce a torque which in effect tries to elevate the system at its boundaries, but at the same time also tries to push it down at the centre of rotation. This can be seen as the production of *anti-gravity* at the boundaries of the rotation plane, accomplished by the production of precisely the same "amount" of *gravity* at the central point of rotation. The net result is therefore null in terms of elevation (translation), and the effect is reduced to a simple rotation. We have therefore shown that the problem to resolve in order to get *anti-gravity* by these means is to break the anti-symmetric behaviour of these two forces in a way so that they produce only *anti-gravity*. These challenge is somehow similar to transforming a pure rotation into a translation. Could it be possible to achieve this? Our optimism lets us suspect yes. But, in parallel to these thoughts other sort of thoughts arise in our mind: for example, would Einstein unveil his $E=mc^2$ if he could suspect before that two terrible bombs would soon be dropped in Hiroshima and Nagasaki? In the problematic world of nowadays, we believe many scientists pose, or at least should pose, themselves such a question.

**Author's Biography:**

J. Manuel Feliz-Teixeira graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc in Mechanical Engineering and a PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology, to, more recently, the simulation of complex systems in management science, like warehouse, supply chain, urban traffic, metro networks, etc. His PhD thesis is on "*Flexible Supply Chain Simulation*". Lately he is also being dedicated to researching new approaches for renewable energy, as well as trying to relate *anti-gravity* phenomena and Classical Mechanics.

***References:***

1: Marc G. Millis, Nicholas E. Thomas, "*Responding to Mechanical Antigravity*", NASA/TM, 42nd Joint Propulsion Conference and Exhibit, 2006

2: Ignor Witkowsky, "*The Truth About The Wunderwaffe*", European Historys Press, 2003

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# Wind-Splash-Turbine[1]

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KEYWORDS: wind energy, wind systems, torque, drag, lift, splash effect.

**ABSTRACT**

Designing a turbine usually implies the assumption that the turbine aerodynamics somehow have to blend well into the fluid flow, in order to obtain good efficiency and a low pressure operation of the overall system. The solution presented in this article points to the opposite, since it is based on the *splash* effect observed when a drop of liquid falls down on a perfectly elastic surface. Although only a small model of a wind turbine has been constructed to validate the concept, here we present and discuss such a proposal by means of mixing some *Physics* with some exercises of *intuition*.

## 1. **Introduction**

People who used to operate the old windmills for grinding grain used to say that one has to let the wind pass through the area of the turbine in order to allow it to turn. This idea is usually understood both for horizontal and vertical turbines, and assumes that the average direction of the flow in the plan of the turbine should remain the same as the direction of the incoming wind. So, it is also usually expected that the wind machine will induce a minimal change in the direction of the flow in its vicinity. Although the idea works, and allows around 30% efficiency, that is somehow looking at a turbine as if it was an aeroplane. There must be some sort of aperture in the collector's area through which the fluid will travel to the other side, that is, to the free space. From this, it obviously results that the effective area of contact with the fluid will be smaller than the circular theoretical area normally considered in the calculations. Since in the present context a turbine is a mechanism to collect energy with the maximum possible efficiency, we may question the advantage of loosing such an amount of energy. Even knowing that the speed of rotation helps the process of capturing the wind, wouldn't it be more interesting if all the wind reaching the turbine's surface could be used to drive it? To go further in the discussion it is important to review some aspects related to the forces driving a wind machine.

## 2. **Wind force, drag, lift, and resistance to rotation**

As said in a previous article, usually the wind turbine design is a complex process taking into account the interaction between an incompressible fluid flow and a solid structure. Frequently, the *Navier-Stokes* equation is used, which relates the various sources of force and computes a distribution of velocity. We believe, however, these equations are mostly appropriate as optimization tools, instead of

[1] It is the author's wish that any new ideas and systems presented in this article will be considered *anti-patent*. This means anyone has the right to use them or replicate any of the described systems for free, without the need for any special permission. If used for business, however, those interested have the duty of contacting the author in order to obtain such permission and to negotiate the appropriate compensation.

being fundamental tools. Fundamental interactions may be understood based on the principles of *energy-conservation* and *momentum-conservation*, while looking at the wind as a huge field of little *wind-particles*. Lift, a typical effect from a solid moving through a fluid, can even be imagined if we think of all those little *wind-particles* as linked to each other by a force of cohesion. The most important analysis of a turbine design may therefore relate the force of the wind with the energy captured by the machine, which highly depends on the *drag* and *lift* effects. The next figure shows the basic effects considered in a wind turbine, which design is frequently reduced to the design of its blades.

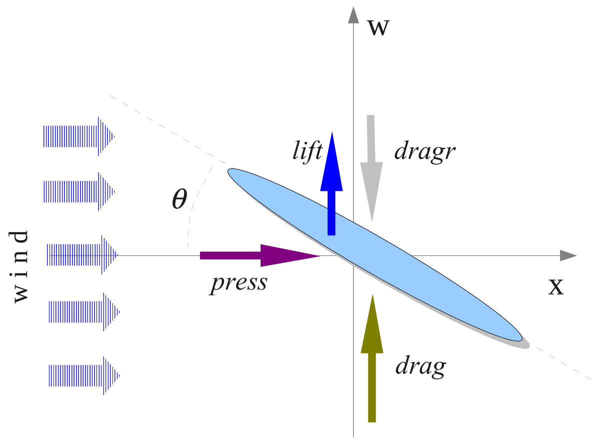


**Fig. 1** Basic effects on a blade of a wind system.

Notice that '*x*' represents the direction of the incoming wind, while '*w*' points to the instantaneous direction of rotation, which somehow can be seen as a 'circular' direction. The machine rotates along this direction. The arrows shown in the figure represent the main reaction forces to the impact of the wind in the blade. Notice that *drag* and *lift* are responsible for inducing torque in the machine, while *dragr*, the force produced by the resistance of air against the blade when it rotates, is in fact the main source of resistance to its movement, acting therefore as an anti-torque effect. Usually, the blade design is optimized in order to find the best possible ratio between *lift* and *drag*. The force we named *press* is simply the pressure imposed on the blade in the direction of the flow. It contains the direct pressure of the wind on the blade and also the projection of the original *lift* (which in fact is perpendicular to the blade surface) in the '*x*' direction, usually called *induced drag,* in aeronautics. The rigidity of the turbine, and also of the structure of the machine, must be able to support this force even in the worst conditions of operation.

Of course, to handle all these effects together is not an easy job, but there are, in our opinion, some directives that might be followed in order to produce a good wind machine: *maximize torque; minimize resistance to rotation; ensure resistance to storms.* For now, let us think on a horizontal circular turbine:

Maximize torque: this would be achieved if we would concentrate all the *drag* contributions far from the centre of the turbine, in its periphery. Standard turbines cannot do this, since this would also imply a huge increase in the overall *dragr* affect. A standard turbine would stop, in that case.

Minimize resistance to rotation: this would be achieved if the angle between the blade's surface and the direction of rotation (w) would be made very small, thus implying an high angle of attack ($\theta$). In a standard wind turbine this is achieved by twisting the blades as they get apart from the centre, but this also reduces the *drag* contribution and the capture of energy.

Ensure resistance to storms: this is a complex issue. Due to the cubic dependency of the wind power on the speed of the fluid, this is the main problem for wind turbines. Stop the turbine (make it a wall) to avoid huge forces due to angular momentum variations, turn around the system in order to face the minimal wind power, and wait for the crisis to pass. This is what standard big turbines do, in general. Smaller turbines may also try to withstand the storm, with the generator stopped (shunted).

For the moment ignoring the third aspect, since it mainly depends on the structure of the machine and on the policy of its operation, the relevant question is: can we find a way to design a turbine in which *maximizing torque* will be almost independent of *minimizing resistance to rotation*? Or, in other words, is there any design in which *lift+drag* could be made almost independent of *dragr*?

In any standard turbine there always has to be a compromise between these concurrent and opposite effects. But, what if we think on a wall? In a compact wall of a building, for example, which can be made resistant to wind storms, what happens to the energy coming from the wind? Is it simply transformed into other kinds of energy, like heat, deformation, vibration? Probably into all these kinds, but what if we consider the surface of the wall ideally an elastic medium? *Wind-particles* going in the wind direction will reach the surface and try to reflect back in the opposite direction, but, due to the constant pressure of the next plan of *wind-particles* arriving to the wall, they are forced to change their direction of motion into a perpendicular direction. That is, they suffer the interference of *splash effect* which sends them all apart from the impact zone. Let us observe it a bit better:

## 3. **The splash effect**

Intuition is a kind of an educated common sense, we would say. It is what a previously educated mind feels as being either expectable or plausible. 3D space exercises and 3D game visualizations will of course be excellent tools to achieve a good level of intuition. One closes the eyes and then lets the “image” of the phenomenon be produced in the emptiness of the brain, and then try to study it, as a first approach. It is almost like exercising the feelings of being the system itself and not only its observer. Mathematics need to appear later, as a powerful descriptive language allowing not just a representation but also to use deduction. Let us therefore use again intuition in order to try to understand the *splash effect*.

Figure 2 shows, in a simplistic way, what happens when a drop of a fluid under the forces (pressure) of gravity falls onto an elastic surface. Considering we are dealing with an incompressible fluid, which means that the ration between its *volume* and its *mass* is a constant, we can see that practically all the mass which in the instant 1 was moving down, along the gravity pathway, was finally spread through a perpendicular direction in the instant 4.

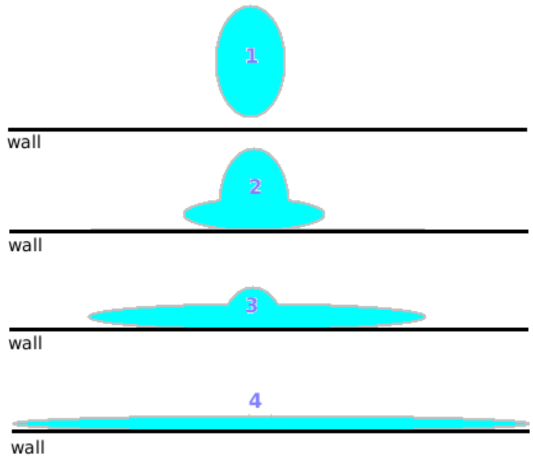


**Fig. 2** Basic splash effect, in a drop of liquid under gravity.

This was due to the “pressure” of gravity, of course. Thus, instead of collecting the energy contained in the drop directly in the midpoint of contact with the wall, one may also collect practically all that energy with sensors located around and apart from that point, where mass is already moving parallel to the wall's surface (see wind example in Fig. 3).

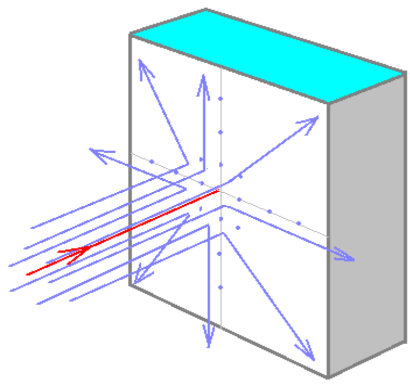

**Fig. 3** Basic splash effect: wind “crashing” into a rigid wall.

This is obviously a promising result in the sense that it let us achieve the possibility of maximizing torque, as previously mentioned, and so we would at this point consider fulfilled the first of our directives for the design of an efficient turbine. Figure 3 shows how the wind will flow when in contact with a rigid wall perpendicular to the wind's direction. We may imagine that this energy could simply be collected by means of a circular system of blades properly positioned at the periphery of the wall. Notice that the efficiency of such a method will be highly dependent on the wall's surface. Ideally, this surface should not absorb any energy from the wind, but only scatter it radially and to the periphery of the obstacle. Thus, in reality the wall must not only be rigid, but also well-polished and made of an appropriate material. Both plastic for cheap turbines and carbon fibre for the more challenging and expensive ones could be some of the materials to be explored. But, while thinking on a very simple and robust solution, one may even use a concrete wall into which a rotating system will be fixed, similarly to what is presented in the next figure, for example.

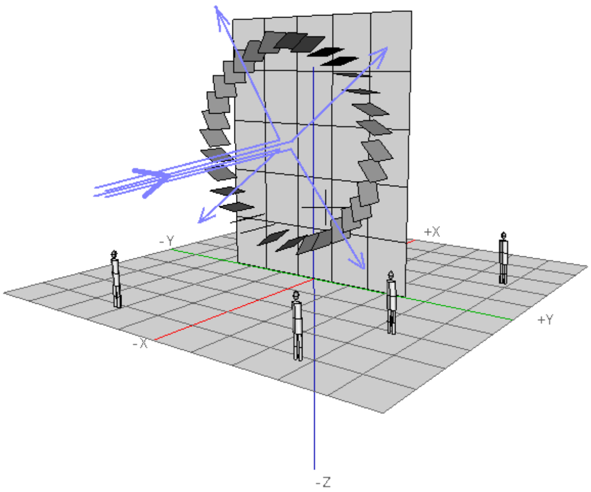


**Fig. 4** Collector for the energy scattered by a rigid wall.

This would enable the construction of very cheap wind sites on the top of hills, for example, or in some places by the sea, promontories, or even offshore. The next figure represents one of these possibilities, something like a concrete building with a big *splash-turbine* placed on it, for capturing the dominant winds. Notice that the "*scatterer*" (splashing surface) does not have to be fixed to the "*collector*" (blades' system), which greatly reduces the weight of the rotating parts of the machine. Another possibility could perhaps be to install one of these turbines on the windiest wall of certain skyscrapers, as long as noise, vibration and people's safety would be seriously addressed.

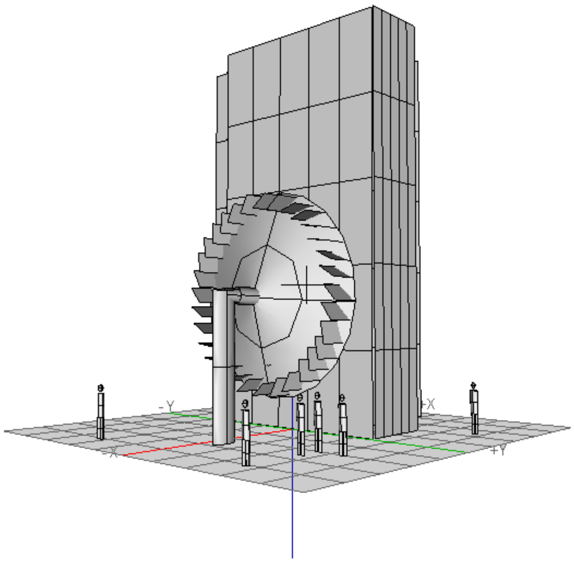


**Fig. 5** An example of a possibility for a wind-splash-turbine.

4. **Efficiency and the blades design**

The fact that most of the energy will be collected and transformed into torque at the periphery of the turbine, seems a good indication that this may result in a system with high efficiency. On the other hand, the mass coming in the wind will be "processed" by the blades of the collector, and this, however, must be done in a way that ensures the minimal resistance to rotation and the maximum capture of forces. Let us try to use figure 6 to represent the effects involved in a collector made of several blades, which then will be mounted in a circle.

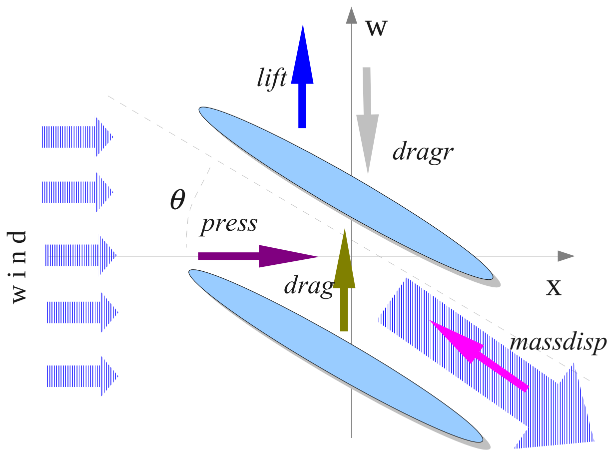


**Fig. 6** Basic effects in an almost parallel blade array.

Now, the wind forces coming from the left of the figure represent the mass scattered radially into the collector. In this *collector*, which may be understood as a circular array of almost parallel blades, as shown in figures 4 and 5, now act the effects of *press*, *drag lift* and *dragr*, but also a new effect (*massdisp*), known as *mass displacement,* which is related to the change of linear momentum on the fluid. This is the effect used for propelling rockets, for example, and it is usually feeble in wind turbines, but it may increase if the blades' proximity do not allow a straight escape of the fluid into the open air. This effect also increases with the pressure inside the turbine, and so with the speed of the wind. It will basically be added to the *drag* effect and oppose the *press* effect, which seems an interesting result, since it also contributes to the forces responsible for the rotation of the machine. We expect, therefore, that by increasing the angle of attack ($\theta$) one can reach a good situation where *dragr* is small when compared with the summation of *drag+lift+massdisp*. Since the overall blade area is also very small compared with the area that receives the energy from the wind, we certainly expect this to be another efficient design. Although it is not altogether new, this design is in effect new as a proposal for a horizontal wind machine. A similar concept is frequently found in vertical ventilators and air exhauster turbines (Fig. 7), for example, which normally are quite efficient and able to operate at very low pressure regimens.

**Fig. 7** Mechanical ventilator based on a vertical blade array.

This is also the kind of design used in some vertical wind turbines, which, unfortunately, have the disadvantage of operating with only half of the wind stream, due to obvious issues of geometry.

## 5. The wind-splash-turbine

Based on what was previously said, several types of wind-splash machines may now be constructed. The art is in the ability to reduce the weight of the rotating part of the turbine, and in ensuring that the collision with the "*scatterer*" will be as elastic as possible and channelling the wind stream into the "*collector*". In the solution presented in figure 8, for example, which is a fixed system, we would think on using thin blades of fibreglass, for example, to build the "*collector*", and perhaps a similar material for the "*scatterer*", this with a slightly conic design for helping scattering the wind flow. All this structure, with roughly 4m diameter, would have to be supported by a strong structure in order to sustain the impact of the wind during any conditions of operation. By its dimensions, we would say this is a machine to be exposed to 7,5KW@10m/s of wind power. If operating with 40% efficiency, that would mean capturing 3,0KW@10m/s. Considering 50% of efficiency on the injection of this power into the electric grid, by means of a generator and an inverter, we finally may deduce this would be a 1,5KW@10m/s machine, in practice. In terms of resistance to storms, in the challenging conditions of 56m/s wind speed (200Km/h), the maximum force acting on the turbine overall would be of around 4800Kg, which seems not to be so difficult to sustain with good engineering.

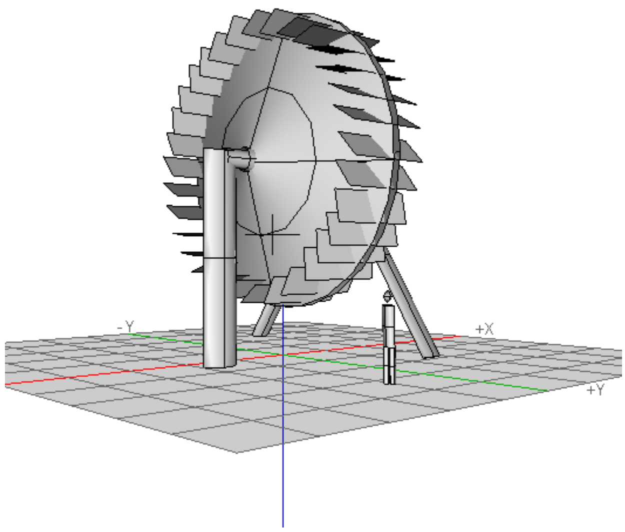


**Fig. 8** A proposal for a *splash-turbine* of 1,5KW@10m/s.

But this design has another advantage: it will always rotate to the same side, no matter the direction the wind is blowing from (see next figure). And this is a very interesting feature, since it allows a continual and steady capture of energy as long as the wind blows. Of course this machine will be most effective in places where there is a preferential direction of the wind, like in mountains or near the sea, for example.

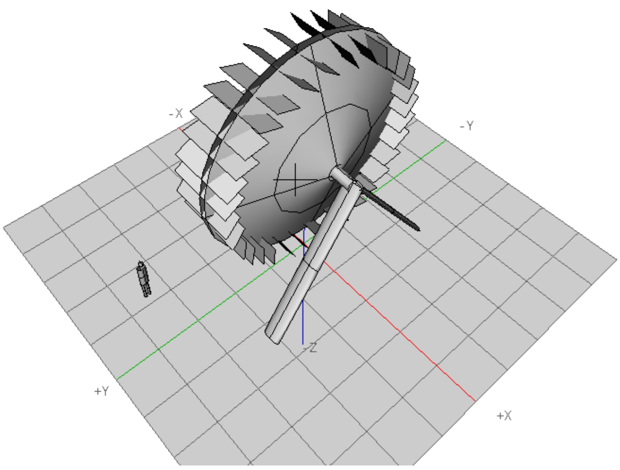


**Fig. 9** Birds-view of the rear part of the same machine.

Another interesting aspect is the easy way for connecting a generator with a high gear ratio to this machine. As suggested in figure 10, this generator could simply be positioned inside the turbine, thus also being protected from atmospheric conditions.

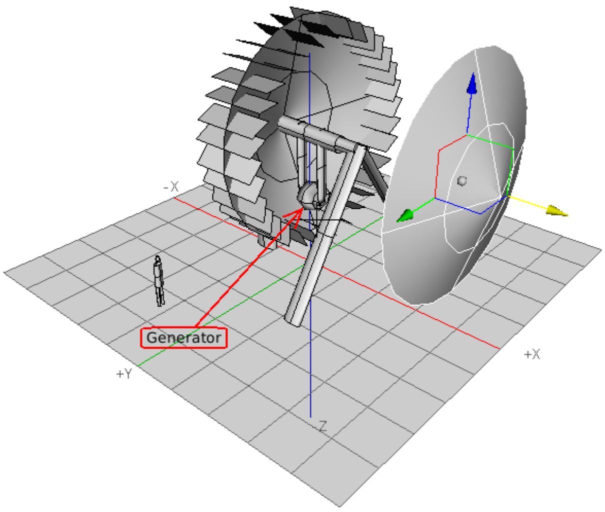


**Fig. 10** The generator mounted inside the turbine.

Apart from these constructions for big turbines, which we defend should be static, or quasi-static, to avoid catastrophic effects during storms, due to the huge torque forces produced by changing their high angular momenta (we are convinced that blades of big turbines crash mainly due to these forces, which are produced even during small storms) other kinds of constructions could be tested, in particular the ones using the idea of an "array" of turbines to achieve a better resistance on handling storms. In effect, it is theoretically advantageous to "disperse" such wind power into several small elements that collect it and transform it into electrical energy (see figure 11). We usually call each of these elements a "*wind-cell*", but they simply are mini-turbines, each one driving a little generator. They may be mounted in the form of an "array" in order to collect the desired amount of energy. Each *wind-cell* can be either fixed or allowed to search for the wind direction. For example, a *wind-cell* of around 0,25m radius (medium bicycle wheel), would receive on its surface during a big storm (@200Km/h (56m/s)) a wind force of around 75Kg. It is not so difficult to build a device capable of handling this. It would be exposed to 0,1W@1m/s and 100W@10m/s.

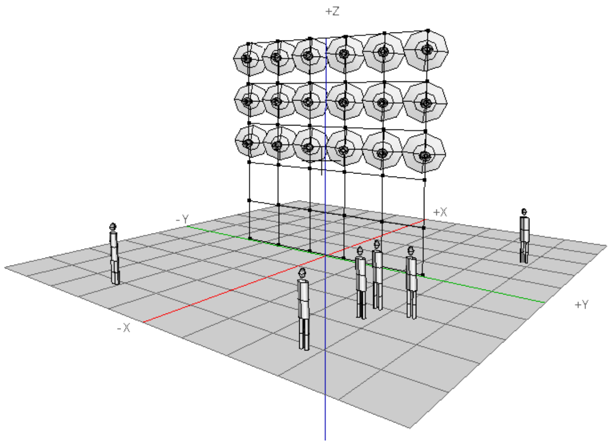


**Fig. 11** Example of an array of 18 wind-cells.

Thus, if the system of figure 11 would be built of 18 *wind-cells* of this type, and if we suppose 40% efficiency for each *wind-cell* (too optimistic, maybe), we could say that this system would capture the mechanical power of 0,4x18x0,1=0,72W@1m/s and 720W@10m/s. Half of this could be injected into the grid!

## 6. Conclusions

Very interesting, but somehow disappointing due to the amount of energy that small scale systems may be able to collect from the wind. The ideas exposed are to be considered *anti-patent*.

**Author's Biography:**

J. Manuel Feliz-Teixeira graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology, to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on "Flexible Supply Chain Simulation". Lately he is also dedicated to researching new approaches for renewable energy.

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# HyperTurbine, a Wind Machine From Another World[1]

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**ABSTRACT**

The wind power mindset has lately been substantially affected by the confrontation between expectations and reality. It has been systematically shown that in practice the amounts of energy produced are much smaller than what seemed to be calculated by technicians who strongly promoted such an idea. We have to say we feel deluded too. The problem has to do with the lack of a clear interpretation of what wind speed means, in practice, in terms of available energy, and also the lack of analysis of the transference of energy along all the parts of the wind system, including its electrical components. A final observation that inverters operate on a basis of 50% efficiency when transferring power, in effect reduces the performance of a wind system claimed to be 30% efficient as half of this. This led us to estimate that most wind systems would be operating with no more than around 15% efficiency, which is a poor figure, specially for small wind turbines. The other aspect is to realize that systems in the market are rated at wind speeds around 10m/s, which in effect means "strong wind", therefore for situations occurring infrequently, in most places. Nevertheless, here we present our latest conception of a wind turbine, which we decided to name *hyperturbine* due to the fact that it is based on a completely new strategy for collecting the wind energy, and on a design we consider even more interesting that the *superturbine* proposed in a previous article.

## 1. Introduction

We found "*a wind machine from another world*" a humoristic title for presenting the unusual method for capturing energy from the wind described presently. It is a case of unusual symmetry. Circular symmetry, normally used for this purpose, both in horizontal axis turbines and in the vertical ones, naturally led people to accept as almost natural collecting the wind impulse by means of some radial element repeating itself around a circle (the blades). Although the same circular symmetry is in effect used in this novel design, we decided to use it in a way that would optimise the amount of 'wind-particles' collected from wind, while minimizing the drag effects opposing the rotation of the machine. Our thoughts are based on a particle-like approach, not on a fluid-like approach. We have not yet even thought about blades. Although such an approach may seem too imprecise for modelling the dynamics of a wind system under high speed winds and fast rotation of the blades, we are in fact interested in the opposite: slow rotation of the machine, and that the system stalls at high speed winds. The first, will ensure the transference of a good torque to the generator; the second will make the turbine seem a 'wall' to the fluid in the circumstance of a storm.

In the following sections we try to explain the ideas behind this new design and present some images captured from a 3D modeller. Although we have built a first scale model of this machine, and

[1] It is the author's wish that the ideas and systems presented in this article will be considered *anti-patent*. This means anyone has the right to use them or replicate any of the described systems for free, without the need for any special permission. If used for business, however, those interested have the duty of contacting the author in order to obtain such a permission and to negotiate the appropriate compensation.

observed in practice how easily it runs even at very low wind speeds, no other prototype has yet been constructed in order to fully characterize the machine. It would be interesting if someone would finance us to build a real machine based on these concepts.

## 2. **Wind force, drag, lift, and resistance to rotation**

Wind turbine design is usually a complex process of calculus taking into account the effects of the interaction between an incompressible fluid flow and a solid structure. These are expressed by the *Navier-Stokes* equation, which relates the various sources of force and returns a distribution of velocity. Although this is an excellent method to estimate the resulting flow of the wind in certain situations, we believe that it is mostly appropriate as an optimization tool, and not as a fundamental tool. In our point of view, the fundamental interactions can be simply understood and described based on the universal principles of *energy-conservation* and *momentum-conservation*, and looking at the wind as being a huge field of little *wind-particles*. Lift, a typical effect from a solid moving through a fluid, can also be imagined if we think of all those little *wind-particles* as linked to each other by a force of cohesion. The most important analysis of a turbine design may therefore relate the force of the wind with the energy captured by the machine, which highly depends on the drag and lift effects. A fair 3D preview of these effects will of course help a lot. The next figure shows the basic effects considered in a wind turbine design, which is frequently reduced to the design of its blades.

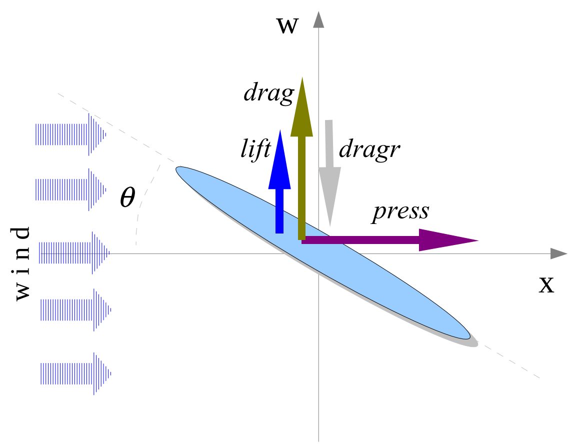


**Fig. 1** Basic effects in a blade of a wind system.

Notice that '*x*' represents the direction of the incoming wind, while '*w*' points to the instantaneous direction of rotation, which somehow can be seen as a 'circular' direction. The machine rotates along this direction. The arrows shown in the figure represent the main reaction forces to the impact of the wind in the blade. Notice that *drag* and *lift* are responsible for inducing torque in the machine, while *dragr*, the force produced by the resistance of air against the blade when it rotates, is in fact the main source of resistance to its movement, acting therefore as an anti-torque effect. Usually, the blade design is optimized in order to find the best possible ratio between *lift* and *drag*. The force we named *press* is simply the pressure imposed on the blade in the direction of its flow. It contains the direct pressure of the wind in the blade and also the projection of the original *lift* (which in fact is perpendicular to the blade surface) in the '*x*' direction, usually called *induced drag,* in aeronautics. The rigidity of the turbine, and also of the structure of the machine, must be able to support this force even in the worst conditions of operation.

As we see, to handle these effects together is not an easy job, and in general one should not expect optimal solutions, since they even depend on several other aspects that are not easily controllable, like wind speed, turbine radius, etc., but also the price of the materials and the feasibility of the technological solutions. There are, however, in our opinion, some directives that might be followed in order to produce a good wind machine. The idea is: maximize torque, minimize resistance to rotation, maximise resistance to storms.

## 3. **The blade design**

Once the previous concepts are well understood, the blade design process can start. As we know, *lift* is stronger than *drag* for small wind speeds and small angles of attack ($\theta$), showing a maximum around $\theta =$ 20º. Small angles of attack, however, imply that *dragr* will tend to be high, since it has its maximum at $\theta = 0º$ and its minimum at $\theta = 90º$. On the other hand, the *drag* effect will have a minimum at $\theta = 0º$, a maximum at around $\theta = 45º$, and again a minimum at $\theta = 90º$. Finally, *press* will exhibit a minimum at $\theta = 0º$ and a maximum at $\theta = 90º$. The problem of an airplane wing is usually a problem of maximizing lift while minimizing press. The problem of a wind turbine blade is more complex. So, what to decide?

Suppose we first want a drag machine, that is, a machine in which its torque is mainly induced by the drag force, with no lift effect. Let us start with the simplest blade design, a rectangle of a very thin material, as shown in the next figure, with an angle of attack of 45º. Notice that the blade rotates to the left, and the '*r*' axis points in the direction of increasing turbine radius.

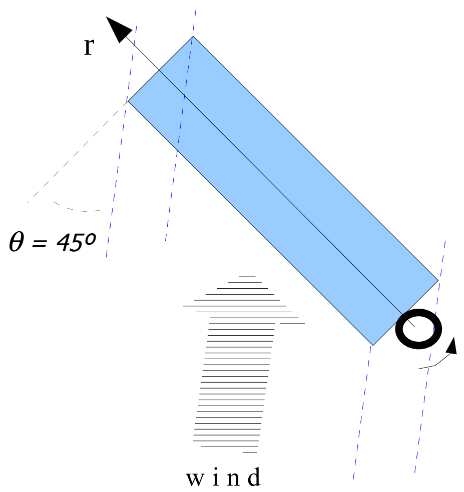


**Fig. 2** Wind attacking a rectangle with $\theta = 45º$ .

Considering the wind force homogeneous, the torque induced in the blade by the wind flow comes from drag effect, which is constant along the '*r*' direction. This would be the only contribution to the torque if the the blade would be stopped. However, if we consider that the blade tends to rotate with an angular speed $\omega$ due to this effect, we must also consider that there will be resistive forces contrary to the rotation applied to the blade. These are what we called the anti-torque forces, due to the dragr effect. In this case, these forces also attack the blade with an angle of 45º, which means they may become a strong effect too. If we observe with a bit more attention, however, we deduce that, unlike the drag effect, dragr is not homogeneous along the '*r*' direction, since it strongly depends on the speed of the *air-particles* reaching the blade on the 'other' side. So, this effect is small for small values of '*r*', but increases fast with the increase of '*r*', since that speed is precisely given by the product $\omega\ r$. On the other hand, anti-torque also increases with '*r*', so, the resultant resistive forces will exhibit a sort of $r^2$ dependency. The larger the turbine the harder it is to rotate it. The faster it runs, the harder it is to raise its angular speed.

The simplest way of minimising these resistive effects is to impose an appropriate geometry to the blade. In reality, everything comes from geometry, even properties like the resistance of materials, the efficiency of military operations, the transparency of water, etc., everything is intrinsically related to geometry, as we know. Geometry may also induce emergence of properties in complex systems, which is why people form teams or clubs, or birds fly in certain formations, for example. In this case, the blade has to be changed in order to capture the most possible energy coming from the wind, while becoming also as 'transparent' as possible for movements in the '*w*' direction. This is achieved, of course, by twisting the blade for increasing '*r*', in order for it to have a $\theta = 90º$ of attack at its tip. This naturally leads to what we call a '*convergent*' design (see previous articles). One may also find interesting that the turbines used in airplane reactors approach this design. We would therefore expect the ideal turbine, or *superturbine,* to have a large number of blades of this type (to capture a lot of energy) as long as each blade is twisted and made very thin, for helping to minimise the dragr effect. The larger the turbine, the thinner the blades should be (low *d*, in the next figure) and the higher the number of blades.

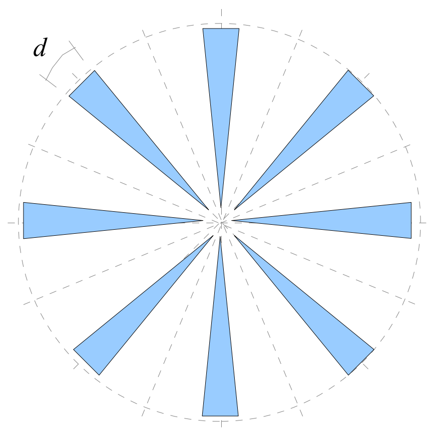


**Fig. 3** Convergent design as an optimised solution.

If we observe carefully, also the blades of the huge modern turbines, installed everywhere, get thinner as they go apart from the centre of the machine. That is obviously a strategy aimed at reducing the effect of *dragr*.

## 4. A design from another world

As we previously said, twisting the blades and making them thinner as they get apart from the central axis of rotation is a strategy for strongly reducing the anti-torque forces produced by the *dragr* effect. This, however, also reduces the overall torque induced in the machine, since the blades loose their ability to capture the wind energy in the periphery of the machine's circle. So, a natural question will be "is there any other way of reducing *dragr*?"

The answer is positive, as long as we forget the idea of constraining the blade design to a radial symmetry. There is, in fact, a big problem in radial symmetry: the blade is forced to move in a direction parallel to its driving force (*drag* + *lift*), which is a situation that obviously creates a strong effect of *dragr*, since the area of the blade receiving the reaction of the air when rotating has the same value of that receiving the energy from the wind. The optimum situation would be a large area receiving the energy from the wind and a very small area of contact with the air in the direction of rotation. As shown in the next figure, this could be achieved if the driving force would be perpendicular to the rotation of the blade. Notice that the blade lies on the same plane of the area of the turbine.

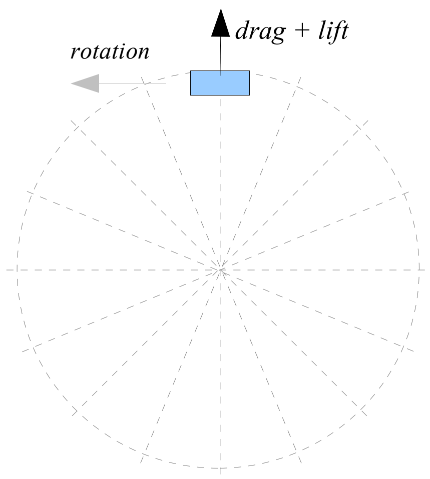


**Fig. 4** Non-radial blade, with its driving force perpendicular to the direction of rotation.

Of course the particular situation shown in figure 4 would not easily induce a rotation in the machine, unless the blade would be drawn with a special design in order to create a certain imbalance between the two sides of the system when the wind blows. Anyhow, if we simply translate the rectangular blade to one side of the central axis, as shown in figure 5, we get something really interesting as a result: the machine will rotate to the left due to the torque induced in its axis by the *drag*+*lift* force, even if these tend to be perpendicular to the blade's direction of movement. One can imagine, for now, the blade 45º inclinated relative to the wind flow.

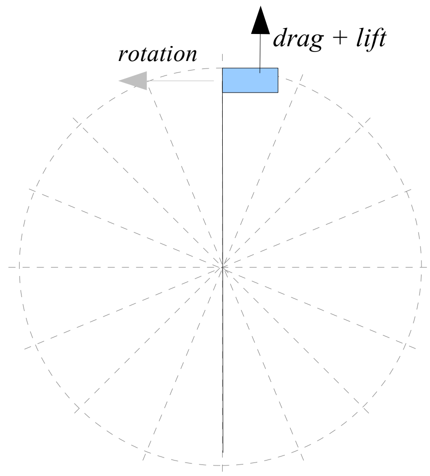


**Fig. 5** Non-radial rectangular blade, inducing torque.

And, since this is obviously a case of squaring symmetry, we should add the same effect to each quadrant of the circle, resulting in:

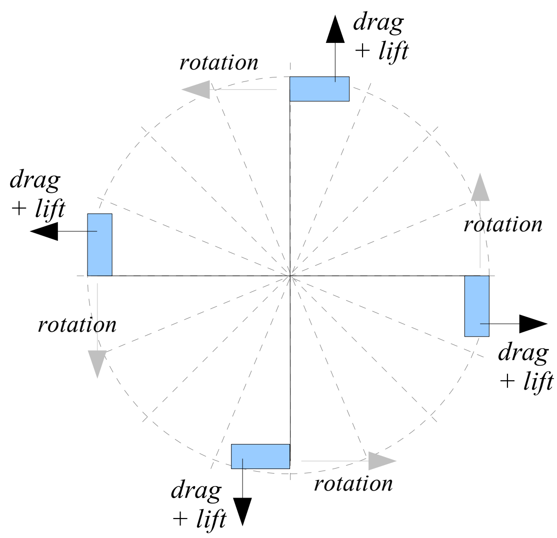


**Fig. 6** Rectangular blades mounted in a squaring symmetry.

It now seems obvious that this type of blade will cut very easily through the fluid during rotation. Obviously, the effect of *dragr* will be almost null at the points of insertion of the blades, even if it slowly increases along the blades' length. This also means that a more general form of turbine can be designed based on such a principle, as shown in figure 7. Notice that all the blades have the same angle of attack in respect to the wind flow, and this angle may even be chosen arbitrarily. A drag machine can be build with this angle being 45º, for example, but a lift machine can also be built, if one chose this angle to be near 20º.

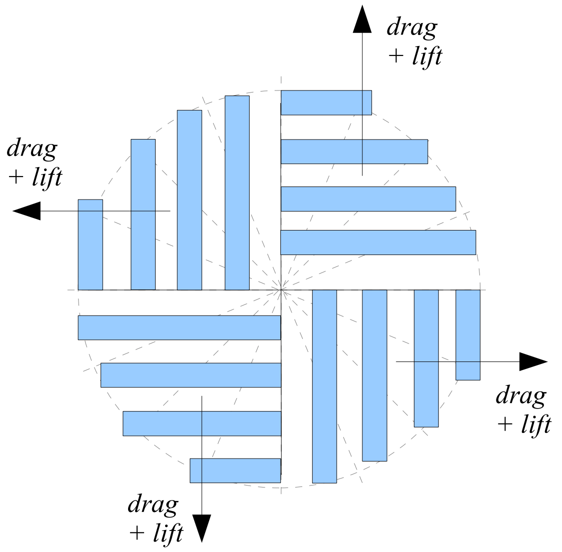


**Fig. 7** Rectangular blades mounted in a squaring symmetry.

One may also notice that all the area of the blades contribute to the torque induced in the system, and that this area can easily be changed either by giving the blades a different angle of attack, or changing the blades' thickness, or even using a different number of blades.

In the limit of simplicity, one might consider a turbine with only two sectors, each of which is driven by a single blade, as depicted in figure 8 (2 sectors, order 1). This configuration, however, seems to have no special properties, since it is another way of representing the common drag turbine. But, if we would raise its order, that is, if we use several parallel blades instead of a single one on each side, and those blades become thinner, the overall *dragr* effect would be reduced. Later in this text we will present a model based on this perspective. By using the four quadrants, however, the *dragr* effect will get smaller, and practically null at the four zones of blade insertion. The order 1 of such a model is also shown in figure 8.

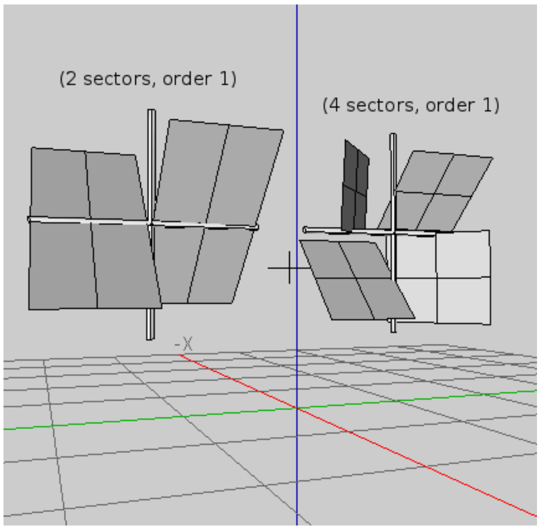


**Fig. 8** Hyperturbines of 2 sectors order 1, the minimal construction; and of 4 sectors order 1, with only a blade per quadrant. The wind is supposed to come from our view.

Higher order designs, however, are expected to be more efficient. Depending on the situations in which the system is to be operated, we would expect an order of blades between 5 and 10 to be appropriate, probably. The model shown in the next figure is an example of order 5.

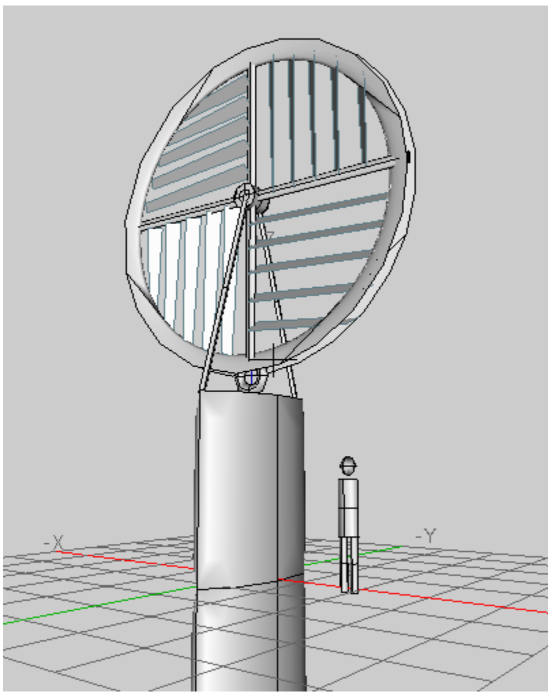


**Fig. 9** *Hyperturbine* of 4 sectors order 5, of 1,5KW@10m/s.

By comparing the dimensions of this turbine with the dimensions of the person, we could roughly say it is a machine to be exposed to 7,5KW@10m/s of wind power. If operating with 40% efficiency, that would mean capturing 3,0KW@10m/s. Considering then 50% of efficiency on the injection of this power into the electric grid, by means of the generator and the inverter, we finally may deduce this would be a 1,5KW@10m/s machine, in practice. Its construction can be made very simple and light, which make us believe it may result in a very interesting and powerful machine. Ideally, we envision a transparent one...

The next figure represents precisely the same machine, but now built with a 2 sectors order 11 philosophy. Notice that it will rotate to the right, as the previous one, and this rotation is simply induced by the two sets of 11 blades mounted in inverted angles of attack. A worse performance is expected relative to the previous design, principally due to the less interesting spatial distribution of the *dragr* effect, as we suppose.

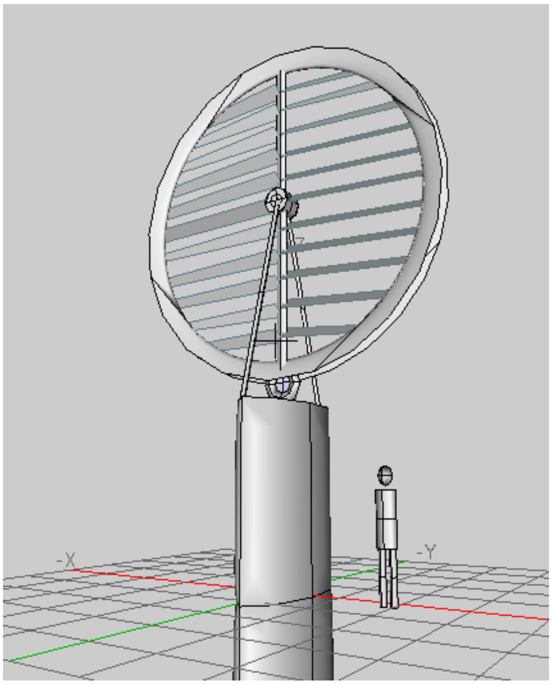


**Fig. 10** Same machine, with a 2 sectors order 11 design.

## 5. The old design versus the new design

One thing we consider appropriate now is to try to get an idea about the performances of these new designs by comparing them with the classical radial design. For that purpose, and avoiding once again the usage of complex mathematical models, we will consider the "*technical performance*" of the entire machine as the ratio between the distribution of driving forces and the distribution of resistive forces. Basically, we may define such a ratio as:

$$TechPerform = \frac{(lift + drag)}{dragr} \qquad [1]$$

This is obviously not a precise metric, but it will help us to have an idea about what to expect from the system, as a kind of holistic estimation. Considering what we have said before, we expect a distribution of driving forces similar to the one represented in the next figure, in the case of the radial style used in the '*superturbine*':

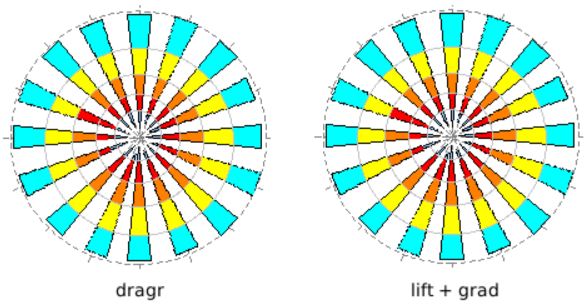


**Fig. 11** Purported *dragr* and *lift+drag* effects in the classical '*superturbine*' design. *TechPerfom* approaches 1.

The expected intensity of these effects is shown as a sequence of colours: *red*, *orange*, *yellow* and *blue; red* being the most intense. Since the blades of the '*superturbine*' are twisted towards the periphery of the turbine, both effects decrease with increasing '*r*'.

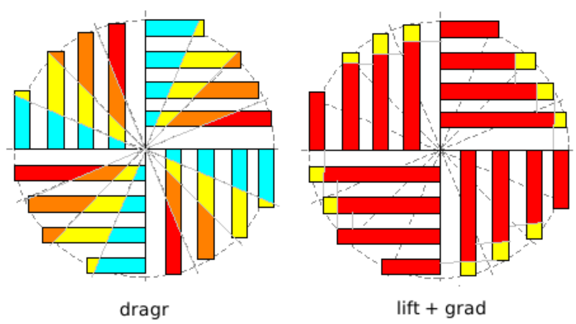


**Fig. 12** Purported *dragr* and *lift+drag* effects in an 4 sectors order 4 '*hyperturbine*' design.

In figure 12, however, is shown what we expect to be the distribution of these effects in a 4 sectors order 4 '*hyperturbine*'. This being true, it becomes evident that although the '*superturbine*' design will show a *TechPerform* near 1, this novel type of design will probably exhibit a *TechPerfom* of around 2, considering the amount of the area contributing to each effect. This would mean a turbine performing 2 times better that the previous one.

Finally, let us consider a 2 sectors '*hyperturbine*', as represented in the next figure. By comparing the two areas, it is expectable that the *TechPerform* of this design will also be around 2. We are convinced, however, that it may be slightly less efficient that the 4 sectors case, due to a larger area of concentration of the *dragr* effect.

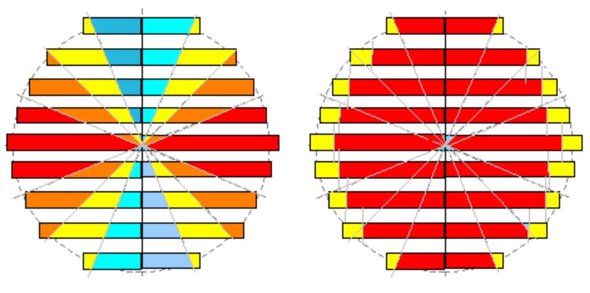


**Fig. 13** Purported *dragr* and *lift+drag* effects in an 2 sectors order 9 '*hyperturbine*' design.

Notice that in the case of *lift+drag*, the blades were also considered to be slightly twisted near the periphery of the turbine. In practice, this will let us regulate the *tip speed ratio* of the machine.

## 6. Why not more than 4 sectors?

Intuitively, increasing the number of sectors would contribute to a decrease of the *dragr* effects, since the area in contact with the fluid in the '*w*' direction naturally decreases. However, it would also decrease the torque induced by the wind in the machine. Taking into account figure 14, where the cases of 2, 4 and 8 sectors are shown, it will be easy to conclude that the torque induced in the turbine will tend toward null as the number of sectors tend toward infinite.

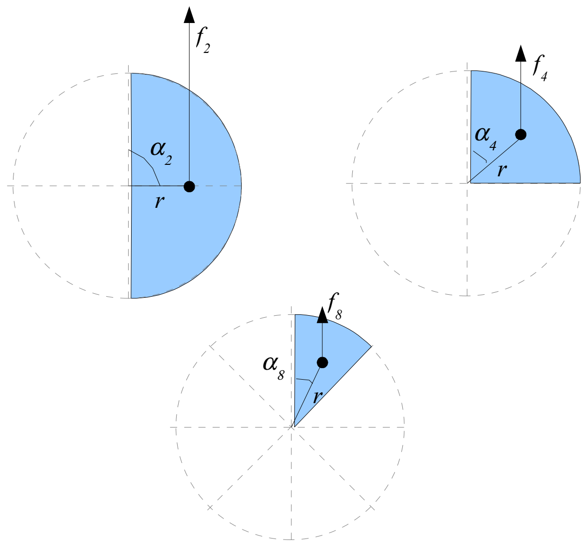


**Fig. 14** Comparison between *lift+drag* forces per sector for the cases of 2, 4 and 8 sectors designs.

Assuming '*r*' practically constant, the effective contribution of these forces to the rotation of the machine is simply their tangential component. Thus, in the first case, the total torque produced in the entire turbine will be given by:

$$T_2 = 2\, r\, f_2 \sin(\alpha_2) \qquad [2]$$

In general, we will have, for *n* sectors:

$$T_n = n\, r\, f_n \sin(\alpha_n) \qquad [3]$$

But then we may notice that $f_4 = f_2/2$, and $\alpha_4 = \alpha_2/2$. This leading to:

$$T_4 / T_2 = 4\, r\, f_4 \sin(\alpha_4) \,/\, (2\, r\, f_2 \sin(\alpha_2))$$

or

$$T_4 / T_2 = \sin(\alpha_2/2) \,/\, \sin(\alpha_2) \qquad [4]$$

Since a2 = 90º, this means T4 will be in fact smaller than T2 by the factor *sin(45º)* = 0,71. By applying the same reasoning, we will deduce that, compared with the 2 sectors case, the 8 sectors will be 0,38 times less powerful, the 16 sectors will be 0,20 less powerful, and so on. So, no power will be collected in the limit of an infinite number of sectors. Obviously. It is also true, however, that increasing the number of sectors strongly reduces the *dragr* effects, and this increases the *tip speed ratio*.

## 7. The situation of stall

Strong wind regimens are the most serious challenge for a wind system as a whole. It is simple to design a turbine and its support structure to operate in a low wind speed situation, but it becomes extremely difficult to project it if one considers winds of, say, above 50 Km/h. The power coming from the wind rises with the cube of the fluid speed, so, also it raises with the same ratio the difficulty of maintaining all that structure up and running. Obviously, in a situation of a storm the best thing is simply to get away from the storm: stop the turbine, turn its surface away from the direction of the blow, and, if possible, wait for the 'crises' to pass. The structure of support must, therefore, play a very important role in this process, since it has to be able to handle all the forces generated in such a situation. Engineering is perfectly capable of doing that, but only if we consider stopping the turbine. Otherwise, the very strong torque effects produced in the system due to angular momentum changes would probably become unsupportable. So, it will be a good thing to be sure that the turbine will simply stop rotating in situations of wind speeds superior to, say, 50 Km/h, that is, the turbine stalls. In the '*hyperturbine*' design this can be adjusted by the separation of consecutive blades, as well as by adjusting the width of the blades. The turbine is expected to stall when the force of the wind acting directly in the face of the blade will be of the same amount as the force acting in the opposite face of the blade, which is due both to the *dragr* effect and the part of the flow 'reflected' by the adjacent blade. This means that we can easily adjust the stall of the turbine to fit our purposes.

## 8. The importance of gearing

It is true that when a turbine without load runs fast and easy with the wind it is a symptom of efficiency. It means that the turbine is able to extract the energy coming from the wind and transform it into rotational energy, which is accumulated by the mass of the turbine in the form of angular momentum. Once this energy is transferred to a load, however, the angular momentum decreases, and the turbine would stop if such a transference would be done with 100% efficiency. Fortunately, the maximum transfer of power between the source and the load is known to happen when the load and the internal impedance of the source have the same value. That is, at an efficiency of 50%. Considering the rotational energy in the first situation (no load) given by:

$$E_0 = ½ \, I \, \omega_0^{\,2} \qquad [5]$$

And the rotational energy with load:

$$E_1 = ½ \, I \, \omega_1^{\,2} \qquad [6]$$

Since we have $E_1 = ½ \, E_0$ , we may expect a natural reduction in the speed of rotation given by:

$$\omega_1 = (1/\sqrt{2}) \;\; \omega_0 = 0{,}71 \; \omega_0 \qquad [7]$$

This is a good result, since it means that in fact we do not have to lose a lot of rotational speed when operating with the optimal load. The problem is: due to the inevitable *dragr* effects, most of the wind turbines are not able to rotate at the speeds typically needed by most generators, which are rated at 1000-1500 rpm. In practice, 300 rpm is already very good for a small wind turbine and something that can only happen during generous wind conditions. This, of course, means the generator connected to the turbine should be able to transfer power with a very good efficiency at a rotational speed of 0,7 x 300 = 210 rpm. In practice, this can only be achieved if we use several very strong magnetic poles and lots of copper.

Notice that there are two main ways of achieving good efficiency in a generator (apart from some geometric issues most of the time easily surpassed): 1) increasing the intensity of the magnetic field; 2) increasing the speed of changing of the magnetic field. So, when one is able to induce only a low changing speed in the magnetic field, then one has no other choice but to increase the intensity of the magnetic field. And that means: more magnets, more weight, more space; and the generator suddenly increases in dimensions and costs; it also means a substantial increase in the consumption of natural resources, precious copper, aluminium, iron, etc. So, why not substitute the idea of intensifying the magnetic field with the better idea of changing it faster; with less magnets, less copper, much less weight, higher transportability, etc.

We strongly defend the usage of gearing between the turbine and the generator. Although this is not so easy to implement in the normal *divergent* systems, due to their configuration of blades, both the *superturbine* and the *hyperturbine* designs allow it, since these may be supported by an external circle that can be connected to the generator by means of a secondary circle (Fig. 15). This way, it is very easy to achieve a gear ratio of 10-20x, which is an excellent ratio for the utilisation of inexpensive generators, most of them available in the market. As we can see from the next figure, an option like this may also contribute to the stability of the overall structure of the wind machine, since it represents another point of support for the turbine.

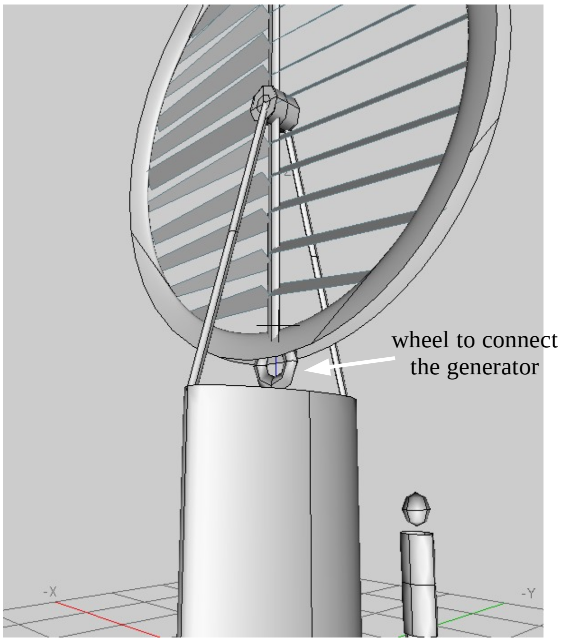


**Fig. 15** Secondary wheel, to connect to an inexpensive high speed generator.

This approach has also the advantage of allowing the turbine to rotate slowly, thus implying less *dragr* effects, higher efficiency in capturing energy from the wind, and maximum rotational speeds around 200 rpm. For this to be perfect, the turbine must be well adapted to the characteristics of the generator. Usually, one first thinks on the turbine and then on a generator to fit that turbine design. The problem, in our point of view, must be addressed from the opposite perspective: show me a generator, and I will design a turbine to drive it.

## 9. **Conclusions**

The ideas presented in this article represent a novel approach for the design and the construction of wind turbines. From the arguments explicated, we believe this sort of approach will reveal a significant increase in the efficiency of collecting the energy from the wind, compared with the current standards. This impression has been supported by the observation of a scale model of a turbine of 1m diameter running with the wind. The new design also represents a very simple and inexpensive method of construction. Anyone interested in building such a machine will be welcome to contact us. The ideas exposed have to be considered *anti-patent*.

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J. Manuel Feliz-Teixeira graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology, to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on “Flexible Supply Chain Simulation”. Lately he is also dedicated to researching new approaches for renewable energy.

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# SuperbWind: An Artistic Wind System Praising the Wind Energy Mindset

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KEYWORDS: renewable energy, wind systems, artistic works, grid connection.

**ABSTRACT**

Herein we present a wind system for low-medium power, developed with the intent of joining arts and low-cost technology. Since both aspects are nowadays easily accessible to the common person, and since the production of energy has already been opened to the private generation of electric power by means of renewable energies, we think that the time has come to motivate people to develop and use their own systems, which sometimes may start with an innocent artistic project. In a certain sense, technology is still being presented to the public as a kind of myth, so, this article may also be seen as a contribution to the popularization of knowledge, against such a myth. We believe that societies would be much more prolific if not trapped in such obstructive practices. Here we present a real artistic-technological system which is now being tested in a real house of a real family. One of the innovative aspects of it is the fact that the generator is located on the roof of the house, instead of on the top of the mast. We expected to be capable of generating electricity for direct injection into the public network and, since the system is located near the seaside, where winds are usually very generous to achieve between 1 and 1,5 KWatt of wind power, in special circumstances.

## 1. **Introduction**

There is no need to remind people in general of the interesting aspects involving the utilization of renewable energies, since the last decades have already shown their importance as clean sources of energy, as well as the substantial amount of power that can be collected directly from natural processes that way. Instead of using destructive principles for generating electricity, which naturally are condemned to produce some sort of waste, renewable systems are there to be almost perfectly integrated with Nature. This is, perhaps, one of the most interesting aspect of the renewable mindset, in our point of view. Humans and Nature should be seen as a single process of development, instead of as a single process of consumption. Symbiosis, instead of dominance, would be the perfect way to go, we maintain.

With the global spread of worries related to climate change claims[1], and mainly the huge jump in oil prices these past years, the interest for searching for innovative methods to produce energy seemed to become not only a global interest, but even a global passion. Several types of systems and proposals are therefore discussed and described on the Internet, created by means of a wide range of technical approaches, materials and apparatus.

Obviously, big energy-producing companies seem to be interested in being the most important players in the field of renewable energies, since they maintain the dominance of the energy know-how and frequently also of the distribution network structures of the countries. Lately, however, following what is already being practised for some years in the most

[1] As we know, some claim climate change is a kind of fashion. Temperatures are rising, no doubts. But, in a certain way, there are some aspects making people wonder if climate, although being dangerously changing in the direction of warming, could also being changed on purpose in the opposite direction, by people that have the power to, at least, try and experiment with it. The global discussion about what is called "*chemtrails*", for example, is an example feeding such doubts. For more, search for "*chemtrails*" in wikipedia.

developed countries of Europe, like Germany, England, and some others, governments are also accepting and even 'inviting' small and private producers of renewable energies to join what they call the *green* adventure and inject their *almost insignificant* production into the public network. They have finally understood that the summation of millions of independent little producers can result in an extremely attractive way of collecting a large amount of very cheap energy, as well as considerably reducing the power lost in the transmission lines connecting long distances. Distributed energy systems are, consequently, on the rise, and the system presented herein may be considered one more element of such a tendency.

There are, however, some notes of interest concerning the artistic aspects of this system: First of all, we also believe that "*there are no arts without science or science without arts*" (Da Vinci). Second, arts are also here as a way to contribute to our commitment to the *anti-patent*[2] concept. Third, this also obviously states that the present system must not be seen as an industrial system, but simply as a technological work of art, and an experimental installation. The *anti-patent* concept is naturally strongly associated with artistic works.

In the next sections we will present the various elements of this wind system, focusing on the three different turbine designs meanwhile developed and used on it, as well as on the mast design and on the link for mechanical power transfer, which allows the generator to be located on the roof, instead of on the top of the mast. Under the *anti-patent* concept, any element of this system can be reproduced by anyone interested in it, as long as royalties are previously negotiated with the author.

## 2. A first glance

Like most wind systems currently used for electrical power generation, the one presented here is based on turbines of horizontal axis. Nevertheless, these turbines are conceived with the concept of *convergent* turbine [1], which we believe to be more efficient than the standard *divergent* approach. As figure 1 suggests, the turbine is mounted on a mast and, by means of a mechanical link, it is connected to an alternator of permanent magnets, which in turn is responsible for converting the mechanical power into electricity. Finally, the electrical signal can be used either to supply a battery bank, injected into the public grid by means of an inverter, or both. The most interesting innovations here are the design of the turbines and of the alternator, and the method for transferring the rotational movement of the turbine to the alternator. Each of theses elements will be described in more detail in the following sections. We have named the entire approach "*SuperbWind*", which also includes three different artistic turbine models: *Elegance*, *Filistine* and *Superturbine*.

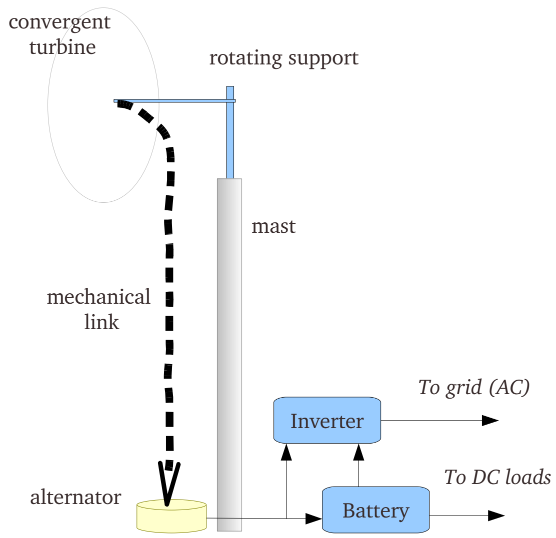


**Fig. 1** Basic elements of the *SuperbWind* system.

## 3. *Elegance*, a very light artistic turbine

Most wind turbines face a problem of weight, mainly due to the materials used in the blades and the heavy metallic central part connecting to the rotating shaft. A standard three-blade turbine of about 2 meters in diameter can be expected not to weight less than around 10 Kg, for example. On the contrary, an *Elegance* turbine of the same diameter weights around 1,3 Kg, that is, almost 8 times less. This basically results from the *convergent* concept, which allows several unconventional blade designs to be used in practice. *Elegance* was the first effectively interesting convergent design (see Fig. 2), since it is very light and allows operating in a wide range of rotational speeds, from 5-10 rpm to near 500-600 rpm. The maximum rotational speed depends, of course, on the generator attached to it, but it is also

[2] Please see more about the *anti-patent* concept at: http://geinsrv.fe.up.pt/feliz/anti-patent.html

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related to the way the turbine is able to cut through the fluid during rotation. Designing a convergent turbine requires a certain ability to sense this effect.

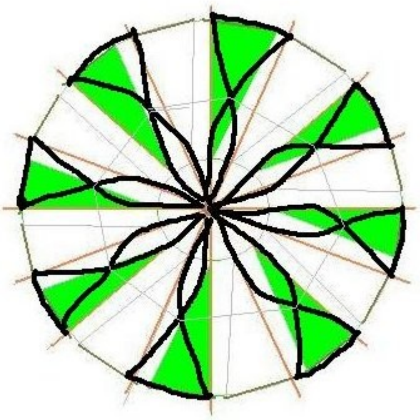

**Fig. 2** The basic idea of the *convergent* design used in the turbine *Elegance*.

Following the proposal of the *convergent* concept, the blades of this turbine are mounted in a way that they are seen by the wind as being somehow 'transparent' in the central zone, nevertheless increasing in 'opacity' to its periphery. This was achieved here by appropriately twisting each blade, which also gives the turbine its elegant appearance (see Fig. 3).

**Fig. 3** A real *Elegance*, 2 meters in diameter.

## 4. *Filistine*, another convergent design

Although the model previously described uses thin fibreglass sticks and tensile wire of nylon in order to acquire its resistance, and its flexibility, in the case of the *Filistine* model the blades are simply made by twisting around a very resistant and light plastic material usually known as *Termoclear*. This structure is then enforced by means of a metallic circumference fixed around the centre and also a tensile and 'invisible' wire of nylon (see Fig. 4). The time for building this turbine is, perhaps, less than the time required to build the previous model, but the costs of the materials, the resistance of the entire structure and its weight increase slightly. *Filistine* is, in effect, a very interesting design, but perhaps not appropriate to handle strong winds due to its larger area of blade exposition.

**Fig. 4** The first *Filistine* model tested, with its 2,5 meters diameter, weighing nearly 3 Kg.

The current model of this turbine has 2,2 m diameter. Although it doesn't have the flexibility of *Elegance* (the previous turbine), it is sa very interesting design for average speed winds. Its name '*Filistine*' (فلسطين) means Palestine in Arabic.

## 5. *Superturbine*, a 1,5 Kg super fast turbine

The *Superturbine* is the last design proposed by the author for wind turbines. The name *Superturbine* reflects the belief that no other horizontal axis turbine will be more efficient than this, due to its advanced convergent design that goes a step further in the direction of the ideal design: an infinite number of blades with null thickness. It is, in effect, a very light (around 1,5Kg) turbine build with extremely light materials, but very resistant to storms. It is basically composed of a metallic circumference connected to a central shaft of nylon by means of tensile wires of nylon too. The blades are very thin and made of a very resistant plastic tape. It is a 1,4 m diameter, very fast turbine. Its depth must of course be adjusted to the minimal torque required to start turning the generator.

**Fig. 5** A *Superturbine* of 1,4 m diameter installed in a real house for tests.

## 6. The mast and the support system

Each of the turbines described has been conceived in order that it may easily be mounted to or removed from the system whenever needed. This process will only interfere with the support of the turbine itself, and not with the rest of the structure, so, it will not be necessary to care about the main mast or even about the generator whenever a turbine is to be removed or replaced.

The solution was to use a tube as the support for the turbine centre, instead of a rod, as usual. A stainless steel tube of 20mm diameter and 2,5mm thick, was strong enough to support these turbines even in strong winds regimen. Under conditions of more power, or larger turbines, however, these dimensions should be set in accordance. Notice that the only object rotating is the turbine itself, its blades, since the horizontal support is fixed, as represented in the next figure (Fig. 6). This tubular support is then fixed to a primary mast which will rotate inside the main mast, thus allowing the turbine to move freely around the horizontal plane while searching for the wind direction.

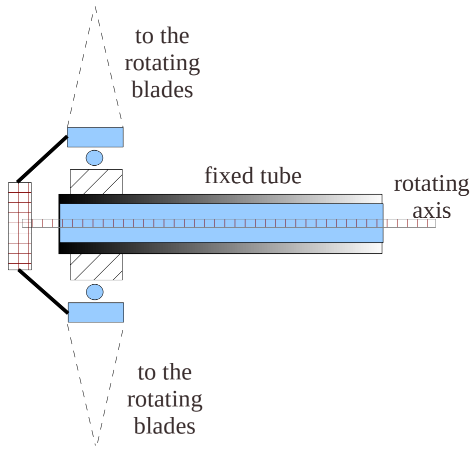


**Fig. 6** The basic connection of the turbine centre to the horizontal stainless steel tube, fixed to the main support. The rotation is transmitted to the inner axis, which moves inside the fixed tube.

## 7. The transmission system

It is more or less obvious now that the rotational movement of the turbine will be transmitted to the generator by means of a rotating axis, and, since we located the generator on the roof of the house, we decided to use a *flexible shaft* for this purpose. This sort of shaft is commonly used in the industry for transmitting average torque between out-of-axis rotating machines, for example. Average quality flexible shafts may be easily acquired at any shop selling machine parts and utilities.

Although there will be a small drop in efficiency in the transmission of mechanical power between the turbine and the generator, we could notice that this method is very compensatory, at least for small wind systems, since it allows building a very simple mast without the need for supporting the heavy weight of a generator at its top. In effect, we assert that the flexibility and lightness introduced by this method is worthy of attention, since it will probably enable the development of other novel solutions for the design of wind systems.

Another very interesting feature is related to the horizontal rotation imposed on the turbine when the direction of the wind changes. As illustrated in the next figure (Fig. 7), transmitting the mechanical power to the generator via a *flexible shaft* allows the turbine to change its direction while capturing the wind without the need to worry about any twisting effects on the system. In practice, a turn of $W_h$ of the turbine on the horizontal plane simply represents adding (or subtracting) a turn to the flexible shaft main rotation ($W_i$), which is much higher, in normal conditions. This allows the turbine to search for the direction of the wind in a very effective and free way.

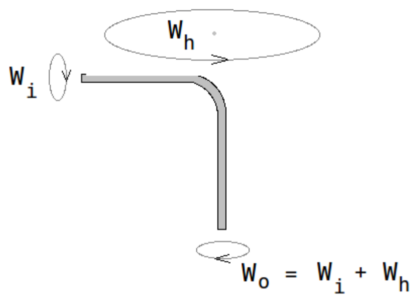


**Fig. 7** Rotation ($W_h$) of the turbine on the horizontal plane adds to the main shaft rotation ($W_i$). Since $W_h$ is normally much smaller than $W_i$, the output rotation ($W_o$) will always be near $W_i$. This eliminates any problems associated with twisting effects.

## 8. The generator

Since it is not easy to find a generator for low rotational speeds, we decided to design and build our own from scratch. The interesting result (Fig. 8), was made of two independent bicycle wheels, one acting as the rotor and the other as the stator. The coils were simply put on and fixed to the stator, and 28 magnets were fixed appropriately to the rotor. This solution turned out to be so simple that we think it needs no further explanation other than the image presented here. The internal impedance of this machine is 3,5 Ohm, it is capable of delivering 1KWatt of electrical power at 600 rpm, weighs less than 5Kg, and the minimal torque to turn it without load is around 0.02 Kgf.m.

There is, however, the need for strong advice to anyone who may possibly be interested in building this machine: any possible hazard due to a split magnet should be seriously considered, therefore the generator must be protected by lateral walls, made of wood, cement, or any other material capable of absorbing the impact of a magnet spinning at near 1000 rpm.

**Fig. 8** *Littledevil,* the home-made generator able to output 1KW at around 600 rpm. It was build out of two bicycle wheels.

**Fig. 9** *Littledevil* (yet without hazard protection) connected via a flexible shaft to a *Superturbine*. Notice that a significant part of the flexible shaft runs in the interior of the main mast. The turbine searches freely for the wind direction.

While the tests of this generator will be completed, we have in mind to optimize certain aspects of it, which are mainly related to the increase of precision in its mechanical structure.

## 9. **Connecting to the grid**

Although this system has been conceived to operate with voltages in a range more or less safe (the generator outputs between 0-80 V), we were also interested in connecting it to the public grid. The first problem arising from this was to find an *inverter* appropriate to this 'low voltage' range of operation. Most of the inverters for grid connection are designed to operate in the range of the hundreds of volts, typically between 150-600 V. These, of course, are inverters to be used with systems designed to produce several KWatt of electrical power, therefore more appropriate for larger turbines. It is somehow a mistake, in our point of view, that *smaller inverters* for grid connection in the range of 300-700 Watt are not available in the market, as this is in effect the range of power that can be produced at home with a turbine with acceptable dimensions for a home roof, that is, 2 m diameter maximum, in order to keep the installation safe and the risks of a mechanical failure low. It is our belief that the appearance in the market of some very cheap inverters (say, 100-300€) for grid connection in this range of '*low power*' and '*low voltage*' would be a success, since people worldwide are waiting for them.

Fortunately, we could find an *SMA Technologie AG* inverter named *WindyBoy* in a 'low voltage' version (*WindyBoy1100LV*), which seemed to be the best option to connect our generator.

Connecting to the grid, however, implies facing some more difficulties in practice, not only technical but economical and bureaucratic as well. At least in Portugal, apart from all the enthusiastic advertising related to the production of *green* energy, which is mostly directed to big energy producers, it seems that small and innovative producers are being frustrated, also due to the fact that technicians on the ground seem not to be technically competent enough to efficiently appreciate some less standard installations. In the absence of knowledge, it is expectable that the process tends to blindly follow the bureaucratic directives, and people may commonly feel trapped in a net of legal little problems.

For example, both *Littledevil* and *Superturbine* are not certified with the symbol **CE**, since they are experimental and home-made systems. Even if their usage will never introduce any problems in the public grid, since they are 'isolated' from it by means of a strongly certified *WindyBoy* inverter, inspectors will focus their attention on this issue and, probably, will invalidate your proposal for feeding the public grid with your *green* energy. But other issues may arise when a small producer decides to connect its system to the grid. Some of them are:

The electricity company will demand the installation of an *energy counter* (see figure 10) in the direction producer-grid. This counter (costing nearly 300€) will be paid by the producer, but the producer seems not to be allowed to move it to another house even if, for instance, he decides to move the production to another place or even sell the house. This is making people wonder whether this is not treating the *counter* as property of the energy company , property that in effect was paid by the producer.

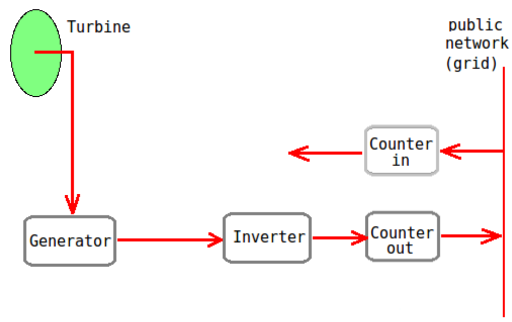


**Fig. 10** Blocks diagram of the basic elements needed for implementing a grid connection. *Counter-in* is the normal energy counter installed in the house. *Counter-out* is the new counter that the producer must buy and install in its place.

This, together with the fact that the present cost of an inverter of 1KWatt is around 1500€, ironically puts the strongest economical pressure on the '*elements for interfacing*' with the grid (and on the bureaucratic processes) more than on the real costs of the technology for capturing the energy of the wind. It is as if we could have the *gold*, but the machinery to refine the *gold* is much more expensive than the *gold*... We believe, anyhow, that the market will soon adapt to the reality and more people can afford to participate in producing their own *green* energy, since this would be a great advance in our world.

## 10. **Some realistic calculations**

Apart from these difficulties, people seem to also be led towards excessive expectations concerning the level of power that effectively can be injected into the grid by means of a small wind system. Catalogues and data sheets of commercial wind systems usually refer to efficiencies of particular elements, mainly the pair turbine-generator. However, as one can see from figure 11, the real case is significantly less optimistic, meaning that any installation of this kind should previously be analysed by an expert.

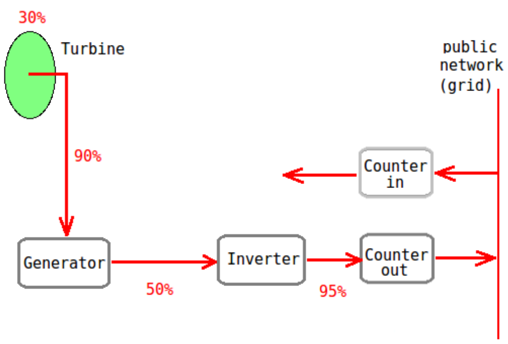


**Fig. 11** Sequence of efficiencies that can be expected when connecting a typical wind system to the grid.

This figure shows the efficiencies of the interconnections of the various elements in a typical wind system. A reasonable turbine will capture around 30% of the wind power received by it. Then, 90% of this will be transmitted to the generator by a shaft. Then, since inverters work in the mode of *maximum power transfer*, half of this power will be dissipated internally in the generator, and the other half will be processed by the inverter. Finally, we may consider 95% the efficiency of injecting the power into the grid by means of the *counter-out*.

A simple computation will obviously show that the efficiency of the complete process will simply be of the order of 13%. A turbine receiving 1KWatt of wind power will inject into the grid only 130Watt: this means a turbine of 2 m diameter under the *generous* winds of around 8,3 m/s (30 Km/h)...

## 11. **Conclusions**

The present artistic-technological system seems to represent an interesting approach for a home wind system, due to its lightness, beauty, flexibility and low costs options. It also shows that technology doesn't have to follow the mainstream solutions offered in the market, and that in many cases the option '*flexibility*' is much more interesting than the option '*force*'. In what concerns the wind, trees understood it. We would probably gain advantages if learning how to 'dance' with the Nature, instead of trying to 'dominate' that which cannot be dominated.

On the other hand, this project also revealed that there are some upsetting issues when connecting a wind system to the public grid, mostly due to the high costs of *inverters* and bureaucratic demands extending further than the equipment of interface.

Nevertheless, this work could also also let us feel that wind is beautiful!

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J. Manuel Feliz-Teixeira graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology, to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on "Flexible Supply Chain Simulation".

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# Circles Model for Metro Light Rail Analysis

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September 2007

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KEYWORDS: metro network, dynamic modelling, simulation and analysis, data projection, abstract domain, public transportation.

## ABSTRACT

The present article shows a way of transforming a Metro Light Rail simulation model into a more abstract model, based on circles. This sort of representation, which goes into the abstract domain, is made to run in parallel with the common dynamic representation of the rail network during the simulation process, and gives the user precious information concerning the harmony with which the overall system is performing. Frequently, a simple look into this running *circles model* is enough to let the user identify or understand certain traffic effects associated with the accuracy of the vehicle scheduling, for example. Although abstract, this is an interesting representation to help study the dynamics of Metro Light Rail networks, together with other methods like sensitive analysis or the common train schedule or time-space diagrams. We also present some results obtained by simulating a didactic representation of the Metro Light Rail of Brussels, since it is a well-known and modern European Union (EU) light rail facility.

## 1. Introduction

Since the last decade the boom in urban traffic was slowly transforming into upsetting levels of congestion, stress, daily delays introduced in the movement of millions of people, and ultimately to unbearable levels of air pollution, one can notice a steady increase in the attraction of the Metro Light Rail as one of the most interesting transport solutions for citizen's flow within and between cities. We can now observe this trend spreading to several places in the world, following the good practice of countries that for a long time already have been prone to using rail transport, such as Germany and France, for example. It is therefore an excellent sign to know that even the emblematic town of Jerusalem is developing its first Metro Light Rail system by now.

It was more or less predictable that with time one should seriously opt for these fairly good quality transport networks in order to reduce not only the environmental impact of people's flow, but also in order to maintain the minimum acceptable quality of life in towns. Too many places in the world are already being confronted with high levels of stress and air pollution, obvious symptoms of a degradation of the life that people live. The price to pay for the compact urban traffic will, therefore, not only be measured in terms of pollution itself, but also, and very importantly, by the health level of the population, since this is the true energy of our towns and cities and the power of our production systems and industry. To replace the myth of comfort of our automobiles for the Metro Light Rail seems an excellent idea, in our opinion.

We have therefore decided to develop a general Metro Light Rail modeller/simulator based on the C++ core code for Supply Chain simulation owned by Feliz-Teixeira (2006), and to upon this create the appropriate interface and the metrics needed to represent and study these types of transportation systems. With such software, several models of real

Metro networks could already be created and tested by simulation[1], making experiments and comparing different policies; for instance, of injecting vehicles in the system. We could also measure some indexes of performance, as well as detect and analyse several unexpected network particularities, like the effect of the operation of terminals or control-lights in the formation of traffic queues, among other effects. All this is contributive to a superior understanding of the entire dynamics related to Metro Light Rail systems, and also to help finding some new ideas about how these systems should be operated. The future inclusion of demand indexes in this simulator is recently being considered, as well.

## 2. Metro Rail simulation

Although Metro Rail simulation is not a matter frequently seen at academic simulation conferences, perhaps because rail problems and its knowledge seem to be relatively stabilised, several software producers are focused on this subject for industrial purposes, training of rail controllers or of vehicle operators, and even for entertainment. *OpenTrack*, for example, is one of the most attractive Object-Oriented tools belonging to the first group, which is dedicated to modelling and simulating complex rail systems for the industrial level. It is quite user-friendly and was created with the objective of answering questions about rail operations, as mentioned by by Huerlimann (2006). Still on relatively the same level but perhaps less sophisticated, one could also point out *RailSim*, for example, from *Systra* (2007), or *RailModeller*, by MacRailSoft for those fond of the Mac Operating System, among others. Deserving reference is also *RailSys*, from Rail Management Consultants GmbH (RMCon), which is part of a more general software system for rail and metro network analysis and implementation (RMCon, 2000?). This tool has extensively been used in projects of Deutsche Bahn, Germany, the European Community, and the Network Rail of the United Kingdom, for example.

Beyond the scope of this article are those systems representing *human-on-loop* (Balci, 2003) simulations or games, as in the case of those tools dedicated to training operators or to entertain, for instance *PC-Rail*, *Microsoft Train Simulator*, and several others. These tools use very detailed 3D visualizations of the vehicles and the networks, and events are made to happen in the simulation in order to induce the operator to react and learn, a common practice found in flight pilot schools.

## 3. The *MetroModSim.exe* approach

Although one could say that our approach (see an overview in figure 1) is essentially on the same level as *OpenTrack*, it is being designed to address subjects more related to the tactical and the strategic spheres, instead of simply the operational. *MetroModSim.exe* may also be used to model and analyse some hard operational issues, like the particular operation of a terminus, for example, but at the moment, and due to the fact that our recent work is more directed at the *administrator* of the network instead of its *operator*, this approach seems the appropriate choice.

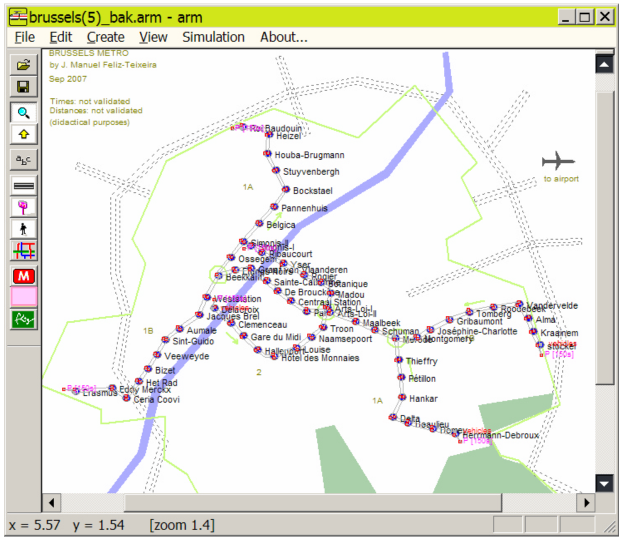


**Fig. 1** An overview of *MetroModSim.exe*, showing a representation of the Metro Light Rail of Brussels.

Besides, in this approach we prefer to focus more on the *limits* of the operational, and not in particular on the operational itself, in order to avoid a direct interference with the engineering of the company who operates on the ground (*operator*), who is expected to own the hard operational information about the network and also the real experts on the matter. We therefore may establish the needs, as well as analyse the impact of certain operational policies in the dynamics of the overall

[1] Due to confidential reasons, we may not present here results obtained by simulating a real Metro Light Rail system recently studied by the author, since it is part of his consultancy activity for a private company dedicated to transport systems.

network, but we will always tend to look at the system from an upper perspective, detecting and evaluating its ultimate performances. How is the customer being served; how many vehicles could probably be saved; how many drivers; estimation of the timetables at each of the network nodes; evaluation of the capacities offered; visualization of traffic effects and detecting unexpected delays: all this can successfully be achieved by using *MetroModSim.exe*. We expect to publish more about *MetroModSim.exe* in articles to come.

The *circles mod*el, anyhow, must be considered a small component of this more general simulation tool, as well as a novel approach for representing *metro-lines* dynamics.

## 4. The Circles model

Usually, people who employ visual simulation tools have a tendency for representing systems as some sort of scaled models of reality, expecting with this to achieve better conclusions and carry out more perfect analyses. When systems get complex, however, such a mimic representation at the model level may induce in the analyst the same kind of complexity that already impregnates the reality, therefore making him/her somehow blind to the essential. Figure 2, for example, represents the Metro Light Rail of Brussels while being simulated in the standard window of *MetroModSim.exe.*

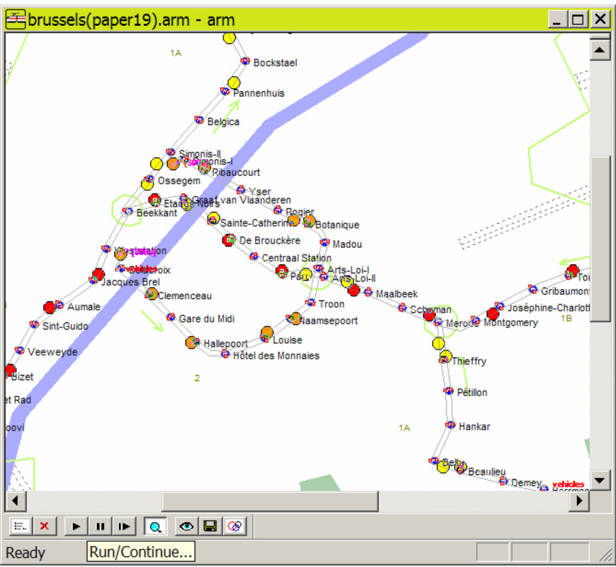


**Fig. 2** The standard visual model, while running.

This is an example of the conventional visual representation of a detailed model running in a simulation window. The network is represented as a net of *arcs* and *nodes* which tend to mimic even the complexity of the space, and the vehicles are coloured circles running along this complex net. In the present case, the vehicles have been distributed by the three *metro-lines* of Brussels Metro[2]: *yellow 1A*, which connects Herrmann-Debroux to Roi-Baudouin; *red 1B*, connecting Stockel to Erasmus; and *orange 2*, around the city centre, linking Delacroix to Simonis.

When the simulation is running, the complexity emerging from this network becomes evident to the eyes of the observer, as one may easily understood from inspecting figure 2 again. In reality, since this kind of *view* mimics also the horizontal geography of the terrain, a clear relation between the diverse vehicles operating in the various *metro-lines* is not easily achievable, since it is obscured by the complexity of the terrain. This is, without any doubt, an excellent representation for detecting bottleneck effects, for example, and in many cases for understanding the behaviour of a certain light-control at a node, for instance, but it fails to give the analyst a more global view on the dynamics of the system, that is, an impression of the global balance/imbalance ratio of the operations. A judicious manager should have access to tools giving him/her such a global perspective on the operations space, since managing the system's parts is obviously not the same as having a wider view and a good understanding of the entire system.

The *circles model* is a method for avoiding such a tendency and to search for more abstract behaviours, or the "laws" which rule the system's complexity. We may consider that this is *projecting* reality onto the *abstract domain*, the domain of the "laws", or, if we are allowed to be a bit more dramatic, the "God's view", free of any superfluous geographic constrains.

So, if we exercise our minds in order to imagine that in effect a Metro network can be seen as a group of different *metro-lines* which may probably interact with each other at certain common points, or nodes, and if we also look at each of these

[2] This model was built with data collected from the Internet webpage of the Brussels Metro Light Rail, but the times and the distances are not real, since they were not crucial for the didactic purpose of this article. Therefore, they have been simply and roughly estimated.

*metro-lines* as a circle, which starts at *terminus#1*, runs to *terminus#2*, and again returns to *terminus#1* in order to reinitiate a new cycle of transport; instead of representing the network as a scaled version of geographical paths and points, as previously, we may represent it as a group of running circles, as shown in the next figure.

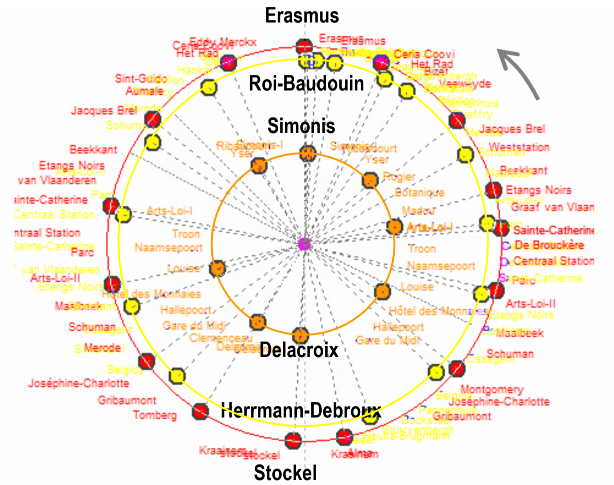


**Fig. 3** The Metro Light Rail of Brussels, represented as a *model of circles*, using *MetroModSim.exe* (3 metro-lines).

These circles, each of which stands for a *metro-line*, with a perimeter directly proportional to the distance of going and returning to the main terminus (*terminus#1*), will sustain the vehicles moving during the simulation in each of the corresponding *metro-lines*. It is therefore extremely easy not only to understand how the overall system is performing, but also to detect any asymmetry induced by some sort of event or procedure, like a deficient operation at a terminus, for example. In effect, one can easily perceive from figure 3 that all *metro-lines* seem relatively well balanced, with their vehicles similarly spaced between each other, which means good stability in the frequency offered to the customers; even if there will probably be some agglomeration in the "*yellow 1A*" line in the access to Roi-Baudouin. The "*orange 2*" line, however, operating with only 8 vehicles, appears slightly imbalanced, since there are some "empty" spaces between certain vehicles. Due to this fact, we may expect less stability in the frequency offered in this line. Notice that the number of vehicles injected in this model has been estimated for the purpose of this article, so it does not probably express the real conditions of operations on the ground. A serious analysis would, of course, require collecting and validating the appropriate data.

Mathematically, however, there are also some interesting results emerging form this *circles model* point of view, like the calculation of the *optimum number of vehicles* that should be injected into a certain *metro-line*, the calculation of the frequency change effect when changing the length of a *metro-line*, how balanced the network is performing, etc., but we expect to treat these mathematical aspects in some articles to come. For the moment, we would simply present some more considerations about the "*orange 2*" *metro-line* of the Brussels network.

## 5. The *orange 2* imbalance, and its correction

As an exercise, we invite the reader to focus the attention on the "*orange 2*" line, which dispatches people around the city centre, as one can see from figure 4.

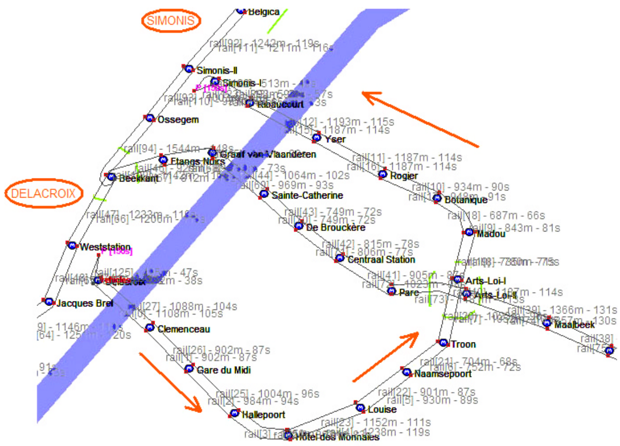


**Fig. 4** The *orange 2* line, serving the centre of Brussels.

In order to better illustrate the idea of the *circles model*, and to make some experimentations by simulation, we have decided to model this *metro-line* with origin in Delacroix (*terminus#1*), where the vehicles have been injected, and with destiny Simonis (*terminus#2*), where the vehicles were to invert in order to start operating in the opposite direction. After some rough calculations we have chosen to inject 8 vehicles into this *metro-line*, separated by around 7,5 minutes, as a first bet. The simulator was then made to run for nearly 3 hours of operations, leading to the following frequency figure offered to the customer:

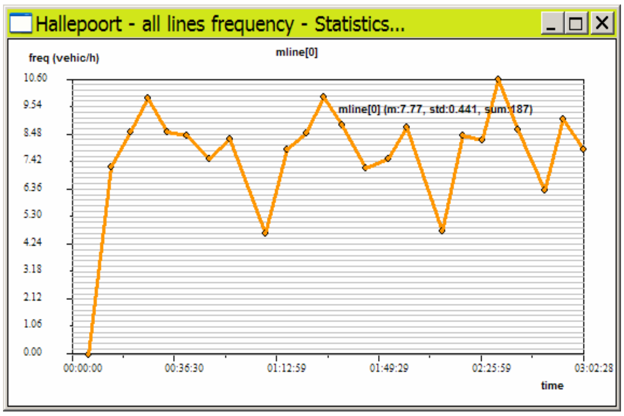


**Fig. 5** Frequency offered to the customer (*orange 2*).

This means that an average of 7,8 vehicle/hour could be expected by the customers of this *metro-line*, with a deviation of ± 1,8 vehicle/hour (in a 4σ confidence interval).

But, if we now inject one more vehicle into this same *metro-line*, the resulting *circles model* already shows a better balanced situation (see Fig. 6).

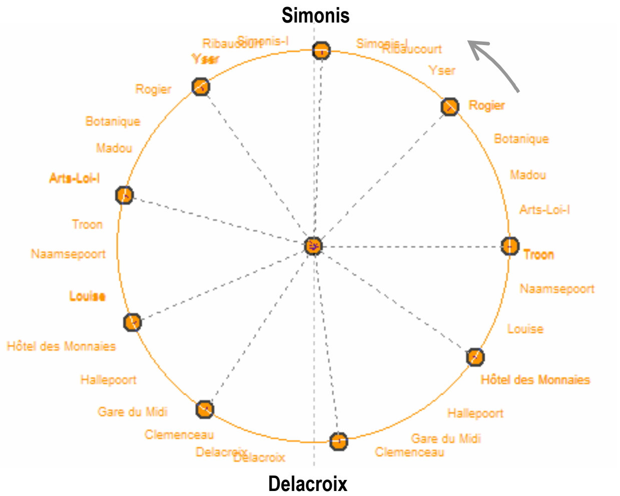


**Fig. 6** Circles model of the *orange 2* line, operating with 9 vehicles separated by nearly 7,5 minutes.

At the same time, an obvious and slightl increase in the frequency offered to the clients was also observed, as shown in figure 7.

This simple examplemakes clear the potential available in the *circles model* method for analysing not only a metro network but also several others transport systems. We expect to soon also apply it to bus and rail simulation, for example, and probably it will even make sense to use it in airport and pedestrian studies.

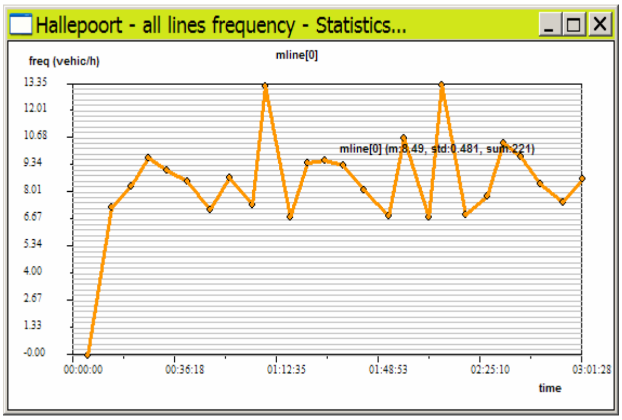


**Fig. 7** Resulting increase in the frequency offered to the customer, in the *orange 2*) line.

We believe, however, that the perspective of *projecting the reality onto the abstract domain* is the most important idea contained in the *circles model*, since it may be an excellent way to try to understand the complexity of the systems we operate and that surround us.

## 6. Conclusions

The results obtained in several practical studies, and in particular with the didactic simulation of the Brussels Metro Light Rail presented in this article, are leading us to believe in the great utility of the *circles model* method. We consider this method a sort of *projection of the reality onto the abstract domain*, and an extremely useful representation to explore and understand the subtle "laws" which frequently impregnate dynamic systems, but can be obscured by an excessive tendency for representing the phenomena simply as they appear to our eyes. We advocate that a better and superior understanding of the complexity can be achieved by looking at the reality in the perspective of a more abstract mindset. In effect, as was shown in this article, a simple look into the running *circles model* of a *metro-line* is frequently enough to let us understand its main problems and identify certain ways to solve them, mostly based on the simpler idea of a *balanced/imbalanced* ratio.

Besides, the *circles model* view is also leading us to understand that a *metro-line*, like a bridge or a molecule, has a certain *proper frequency* for being operated, which may be seen as the frequency to which its imbalance is minimal. More than that will represent too much pressure on the *metro-line*; less than that will mean too little pressure on it.

Finally, we would be pleased to receive any comments or feedback about any experiments based on these ideas.

**Author Biography:**

**J. Manuel Feliz-Teixeira** graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology to, more recently, the simulation of complex systems in management science, like warehouse, supply chain, production systems and transport systems. His PhD thesis is on "Flexible Supply Chain Simulation".

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# Void Pointers to Event Handlers and Simpler State Diagrams

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KEYWORDS: entity, activity, simulation, event, event handler, state diagram, C++, executive.

**ABSTRACT**

Here we discuss one of the possible effects of using *void pointers* as arguments to *event handlers* in the *event scheduling* simulation approach: a simpler representation of the state diagram of the system, and a more general concept of *activity*. This is done by taking into consideration an example of C++ code through which the basic elements of a simulation engine are implemented. The method has been used in the recent simulators developed by the author and proves not only very efficient in the process of implementation, but also simpler in modelling the system's state diagram, since the *queues* between *live activities* are no longer "needed".

## 1. Introduction

As schematically represented in figure 1, the basic engine of an *event scheduling* simulation approach is supported by three main elements: an *event list*, which contains by order of execution the events to happen in the system; a *simulation loop*, also known as *executive*, which is responsible for the maintenance of the time and to order the entities in the system to execute the correct events; and the function or method *Schedule()*, which is used by the entities to insert (schedule) future events into the *event list*. As we know, this mechanism allows the establishment of a circuit of information which results in the *simulation cycle*, as shown in figure 1:

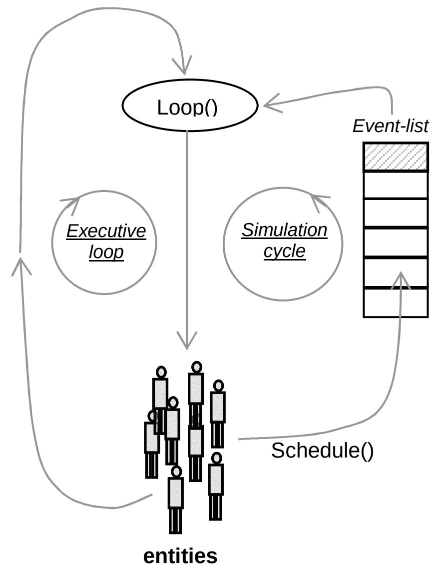


**Fig. 1** The basic elements of an event scheduling simulator engine and the simulation cycle.

On the other hand, in its most common form, and mainly under an object oriented programming structure, an *entity* is due to own not only a group of attributes (see figure 2), but also a group of functions or methods representing the actions to take in each of the events that the entity processes. These methods are called *event handlers*, and normally are accessible from outside the entity through a call to another method, the *dispatcher*, which simply chooses the handler to execute based on an event identification (*EventID*). Here we call this method *Execute()*, a method that belongs to the basic entity structure represented in the figure:

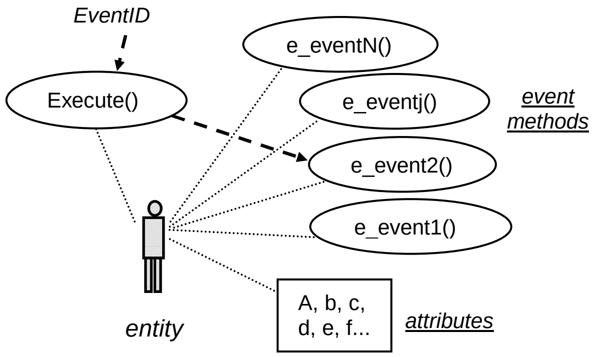


**Fig. 2** Attributes and methods of a generic entity

Thus, in order to stimulate the execution of a generic event handler *e_eventj()* of a generic entity *entity*, the simulation's *Loop()* method has only to use a statement of the type:

```
entity->Execute(eventIDj);
```

Then, in the body of the method *Execute()*, the entity will decide the appropriate handler to be called. A very simple way of doing this is to write the *Execute()* method of the entity as something like:

```
Execute(int id)
{
 if(id==eventID1)
   e_event1(); //call handler 1
 else if(id==eventID2)
   e_event2(); //call handler 2
 . . .
 else if(id==eventIDj)
   e_eventj(); //call handler j
 . . .
 else if(id==eventIDN)
   e_eventN(); //call handler N
}
```

Anyhow, this scheme does not allow the passing of any information to the event handlers through the mechanism of the event list. So, the handlers are somehow "separated from the past", and the result is less flexibility of the code, more complexity, and less advanced operations. This problem is indirectly related to the sort of structure used in representing the *event* object, which is the object to be stored in the event list. The following basic *event* structure was used in the first versions of our simulators:

```
class Event
{
  float      m_time; //event time
  UINT       m_event; //event ID
  Entity*    m_pEntity; //entity
};
```

And the method *Schedule()*, following the same kind of logic, had the form:

```
Schedule(float time, UINT event, Entity* pent)
{
 //body
}
```

2. **Passing general data through the event list**

In the previous scheme, as we noticed, no data could be directly passed from the *past* into the *present* (or from the *present* into the *future*) throughout the event list, since neither the handlers nor the *event* structure were prepared to receive and to transfer such data. In a dynamic simulation approach, however, and in particular when using a strategy for representing the system's functionality based on a sequence of procedures (as it is the case of discrete simulation), such a facility would in many cases be extremely advantageous, and that is for sure the reason that led some authors to advance their simulators in such a direction. Already in at least the 1990s, Howell, in his discrete simulation library for C++, was using a version of the *Schedule()* method with 5 arguments, in which one was precisely a *void pointer* (Howell, 1997). By means of this pointer, general data can be transferred through the event list mechanism, as long as both the *Schedule()* method and the *event* structure are properly modified. Not precisely in the same way of Howell, who later developed SimJava, a simulation package for modelling in Java (Howell & McNab, 1998), but also with the idea of passing data into event handlers, others like Darmont, in his DESP-C++ simulation package (Darmont, 2000), for example, have used a similar idea.

We may therefore recognize that the initiative is not new, at least in terms of transferring data throughout the *event list*. However, let us take a deeper look into another perspective: the design of the state diagram of the system (or activity cycle diagram). For that, we will consider the following new version of the code, which already makes use of a generic *void* pointer *ppp*:

```
class Event
{
  float       m_time; //event time
  UINT        m_event; //event ID
  Entity*     m_pEntity; //entity
  void*       m_ppp; //generic pointer
};

Schedule(float time, UINT event, Entity* pent, void* ppp)
{
 //body
}

Execute(int id, void* ppp)
{
  . . .
 else if(id==eventIDj)
   e_eventj(void* ppp); //call handler j
 . . .
}
```

When the simulation's *Loop()*, or executive, will remove from the head of the *event list* the next event to be executed, it can easily send it to the appropriate *entity* by means of the following statement, which obviously includes the *void* pointer, and therefore even other entities may be passed to the entity:

```
entity->Execute(eventIDj, ppp);
```

So, the transfer of data pointed to by *ppp* to the correct *event handler* is straightforward, as we can deduce from the previous lines of code.

## 3. The effect on the system's state diagram

From now on, when scheduling an event, one will be able to specify not only the <u>type</u> of event, the <u>time</u> to occur and the <u>entity</u> to execute it, but also which <u>object</u> in particular this entity may handle, for example. This can be very useful for the implementation of complex decision criteria in queue serving, for instance, since it also allows passing *entities* onto event handlers and thus making them jump directly from one *live state* into another *live state*, ignoring the *queue* in between. Only after being analysed, such entities would be sent to the appropriate position in the queue, if needed.

This simple feature results in some interesting changes concerning the form of representing the state diagram of the system, since now we may think in queues *beside*, or even *inside*, live states and not in *serial* with them. That is, a *live state* may directly be linked to another *live state*.

As an example, figure 3 represents the process of imputing materials into a stock facility when using the usual system's representation, with the queues in serial with the *live states*. Events are represented as arrows:

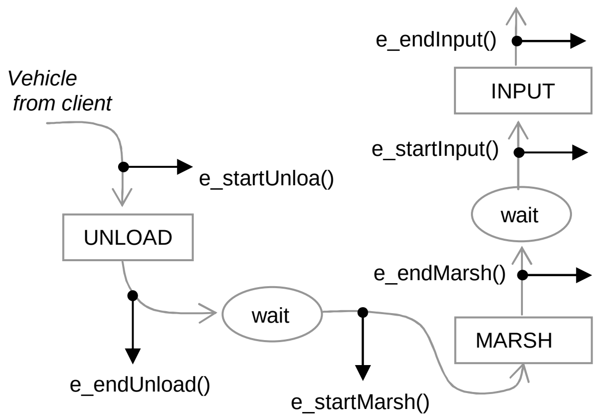


**Fig. 3** States and events in the input stock process

In general, when a *live* activity (or state) ends, the correspondent *entity* is sent to the appropriate output queue, where it will wait for its time to be served by the next *live* activity. This method of representing the logical states of a system is generally accepted by the simulation and modelling community, and a large variety of applications and tools use this as a primitive for their more or less complex approaches. There is even a widely accepted rule stating that a *queue* (waiting state) must always be inserted between two consecutive *live* states. This, however, gives the idea that queues have a certain independence from the live states, even if they in fact exist in order to serve these states. We wonder what a queue would be needed for if isolated, in a desert... So, we claim, in effect, that queues may better be seen as playing the role of interfaces between live states, and so they can be *included* by the live state "object" itself. This also means that the live state will be solely responsible for the handling of its queues.

Figure 4 represents precisely the same process of the previous figure, but now taking into account these considerations. Notice that the queues are now located next to the live states, almost as if forming part of them. This way, queues may even in general be seen as properties of the live states, while each live state links directly to the next live state by means of the event of its ending.

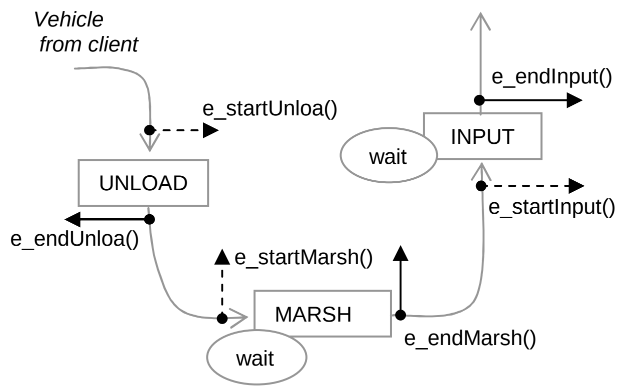


**Fig. 4** New states and events in the same process as of the figure 3.

A closer inspection of this case reveals some interesting aspects. For example, when processing the event *e_endUnload()*, the facility may already directly call the event *e_startMarsh()*, passing to it the order which is to be processed. When this event takes place, it will follow some procedure of the type:

```
e_startMarsh(void* ppp) //order=*ppp
{ if the marshalling queue is empty
   {if the MARSH activity is free
       {send the order to MARSH;
        schedule e_endMarsh(order);}
     else //marshalling activity occupied
       {send the order to waiting queue;}
   }//..............................
  else //marshalling queue not empty
   {send the order to appropriate queue
position;}
}
```

Then, at the end of this activity, the event *e_endMarsh()* will move the *order* to the next live activity (INPUT), by directly calling the handler *e_startInput()* with the *order* as argument, and then restart the marshalling:

```
e_endMarsh(void* ppp) //order=*ppp
{get the order from the MARSH activity;
 call directly event e_startInput(order);
 If the marshalling queue is not empty
   {get the new order from the queue;
    put the new order into MARSH activity;
    schedule e_endMarsh(newOrder);}
 }
```

Notice that in this method only the events of "end" had to be scheduled, and use the *event list*. The events of "start" can simply be called directly, without the need for using the *event list* mechanism. So, in this scheme, each activity may keep its logic private, not accessible to the other activities. At the same time, only the event handlers related to the "start" of activities need to be of public access. The concept of "activity", in itself, may also be now understood as a more complex notion, in effect, as an association of a *live* state with several *waiting* states, as depicted in figure 5:

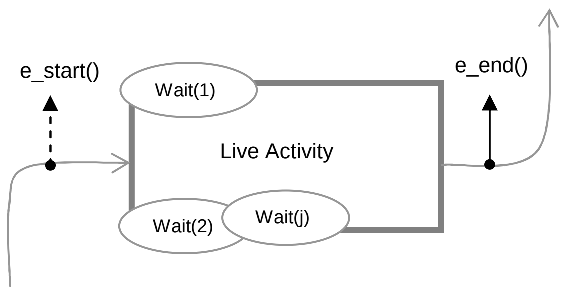


**Fig. 5** The concept of a generic activity, with its several waiting states and the events of *start()* and *end()*.

This approach is now being used in the core of our C++ simulation engines, which led to several modelling and simulation applications specially dedicated to Warehousing, Automotive Traffic, Supply Chain, and, more recently, to Metro Networks simulation and also Manufacturing simulation. More about some of these tools, including the free download of certain simulators, can be learned at: [http://www.fe.up.pt/~feliz](http://www.fe.up.pt/~feliz)

## 4. Conclusions

We may conclude that the method presented in this text is not new in terms of transferring data through the *event list* in the event scheduling simulation approach. In any case, it showed to be very powerful also in what concerns the representation of a system in terms of a discrete model. In effect, the scheme reduced the idea of model to a collection of *live* states (*live* activities) linked by *paths* or *arcs* that define the flow of the entities. The usual queues are ignored. At the same time, a single event handler has to be of public access for each activity, and that is its event of its *Start()*. This event does not have to be scheduled into the *event list*, since it will always be called directly from the simulation objects. Besides, the queues will be considered internal to the activities, and models will start to have the aspect shown in the figure:

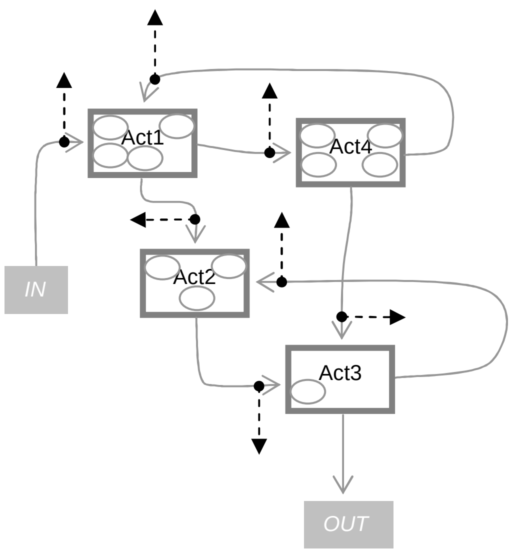


**Fig. 6** A generic model made of four generic activities and their "visible" events.

This approach is being used with success in several simulator engines developed in C++, mainly dedicated to Warehousing, Traffic, Supply Chain, and lately to Metro Network simulation and Manufacturing simulation. The following visual samplings aim to give an idea of such tools, which we usually used in research and consultancy projects:

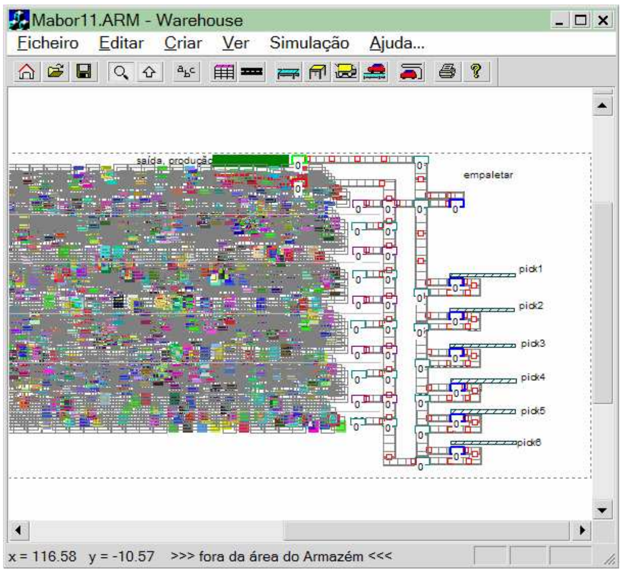


**Fig. 7** A generic view on the warehouse simulator.

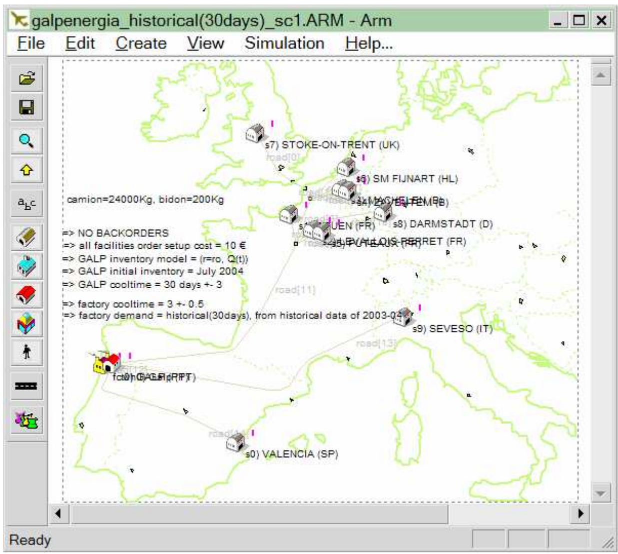


**Fig. 8** A generic view on the supply chain simulator.

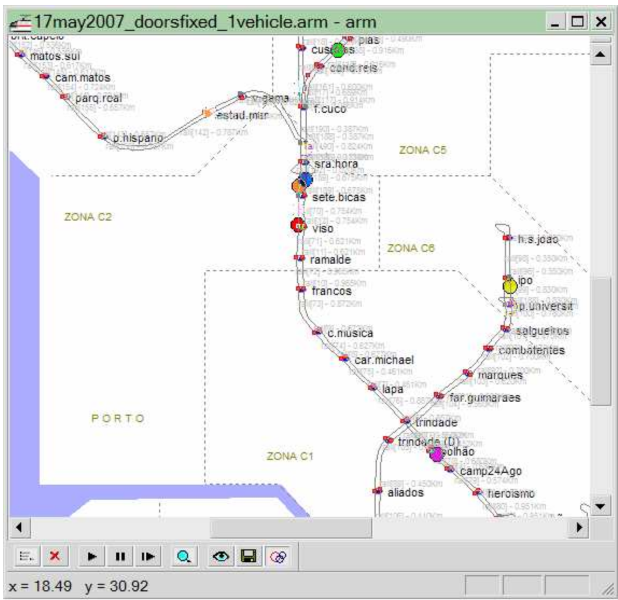


**Fig. 9** The new metro simulator, now being developed for the transport company TRENMO (www.trenmo.com).

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**J. Manuel Feliz-Teixeira** graduated in Physics in the Faculty of Sciences of the University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on "Flexible Supply Chain Simulation".
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# scMod/Sim.exe
# For Supply Chain Modelling and Simulation

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March 2007

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KEYWORDS: supply chain, modelling, simulation, flexibility, event scheduling, computer application.

## ABSTRACT

In this paper we present an application dedicated to modelling and simulating Supply Chain systems (*scMod/Sim.exe*), developed with C++, with which a wide number of structures and policies can be analysed. The model construction is based on primitives resembling the real objects involved in these systems, like trucks, transport paths, retailers, factories, warehouses, stocks, etc. The result is a very simple environment for representing the Supply Chain in a wide range of situations. The simulator application, with its various tools for automatically representing the relevant metrics, gives the analyst an excellent opportunity for studying the behaviour of his/her Supply Chain, from the operational basis to the level of strategic decisions. In addition, the simulator includes a tool for helping to create the *rigidity matrix* of the Supply Chain (Feliz-Teixeira & Brito, 2004), with which the analyst can get an idea about how much his/her system will be *flexible* to demand variations.

## 1. Introduction

Developing a model commonly implies the representation of a system with the help of general purpose primitives, like the basic blocks of logic used in *Petri nets*, *System Dynamics*, UML, etc., or even the wide spread *state transitions diagrams*. Building a model therefore implies the appropriate ability to construct based on such blocks. Of course, today it is easy to agglomerate a certain number of these blocks and assign them the "self" of an "entity", using the properties of inheritance offered by the modern object-oriented languages, for example, but even so the modeller must have some knowledge about the basis behind these approaches, since it is frequently necessary to readjust such "entities" to the specific contours of a project. A substantial number of companies purchase generalist modelling tools with the intent of addressing specific problems, but later realise that it would also be necessary to contract a specialist on modelling, since the system to model reveals itself to be considerably more complex than expected. The usual destiny for such modelling systems is therefore the wastebasket. Exceptions exist, of course, among companies with a high capability for management and contracting, where groups of engineers are specifically dedicated to modelling and simulating the most relevant processes. This emphasis on the simulation as a matter for specialists seems an interesting policy, and for sure the results emerge accordingly.

## 2. About *scMod/Sim.exe*

The double application named *scMod/Sim.exe*, comprised of *scMod.exe* (modelling) and *scSim.exe* (simulation), aims to dissolve the need for special skills in building the Supply Chain model, while at the same time maintaining the need for reasonable skills in handling the simulation process. The entities of the Supply Chain are represented as much as possible as they appear in "reality", thus, no special knowledge is needed to construct a model other than that of creating a replica of the system based on "scaled elements of the reality". This could perhaps be interesting for Supply Chain specialists who have few skills in modelling, but a good background in simulation.

In effect, each object is intended to be seen by the user as an "imitation" of an object existing in reality, with a certain functionality encapsulated, instead of exposed to the modeller. Thus, the level of abstraction required in the process of modelling comes closer to that of a planner. At this level, one does not need to define or represent the dynamics of the internal processes of the Supply Chain elements, since they are pre-defined in the respective objects. The user only has to tailor these generalised objects – named *Customer Supplier Units* (CSU) – in order to represent the particular Supply Chain with the accuracy needed. The next figure shows various CSUs prepared to be linked in a future Supply Chain network.

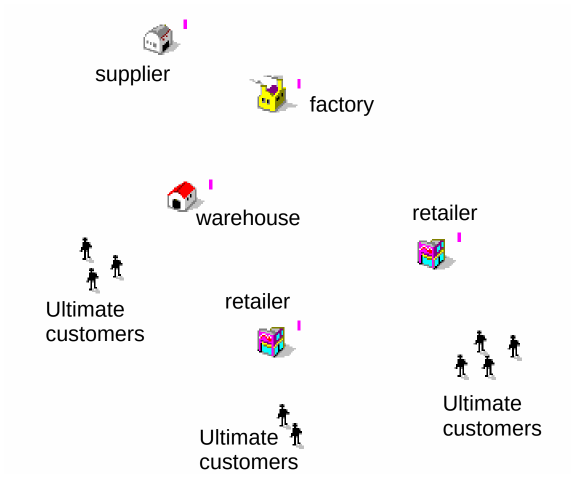


**Fig. 1** Elements for creating the Supply Chain model.

This approach may also be considered a "data-driven" approach, since there is no need for programming in order to model or to simulate the system. The proposal also reflects the tendency of providing the industry with simulators for specific areas of knowledge, trying to imitate the natural specialisation observed in the business world. As there are companies specializing in airport projecting, urban traffic design, nuclear central building, etc., our point of view is that it would be advantageous to reproduce the same tendency in industrial simulation tools, instead of systematically developing models from the basis. This would provide the modelling community with an extensive and very useful "data base" of specific simulators, for specialist planning. A huge data base of highly reliable specific simulators is what we modestly intended to contribute to. More detail on the processes involved in this application can be found in Feliz-Teixeira & Brito (2003) and in Feliz-Teixeira (2006). A visit to the author's website could probably be of interest too:the site can be accessed at http://www.fe.up.pt/~feliz.

## 3. Modelling with *scMod.exe*

Here we will try to give an idea of how easy it is to create a model of a Supply Chain, even when it is to represent a complex network. This will be done with the aid of some images taken from *scMod.exe*, the application for modelling (Fig.2).

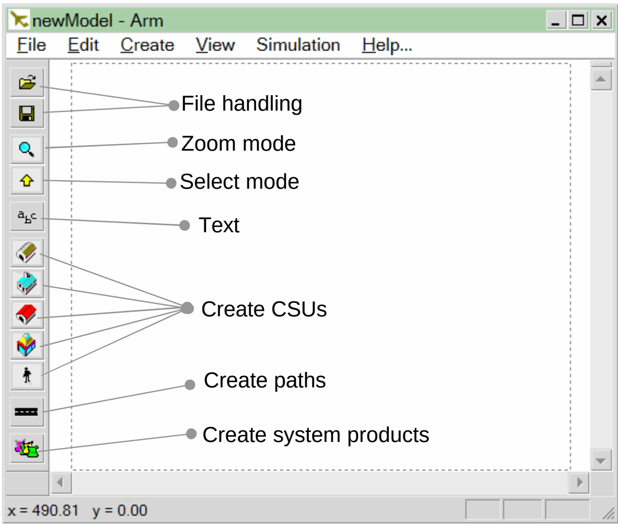


**Fig. 2** A general view of the *scMod.exe* application.

The Supply Chain model will be represented in the application's window with the aid of the buttons of the main *toolbar*, which allows not only the creation of diverse Supply Chain facilities (CSUs), but also the products, sub-products and raw materials available to the system, and the transport paths for connecting these CSUs.

One can basically say that to build the Supply Chain network will be as simple as to place into the application's window the various Supply Chain facilities, that is, factories, warehouses, retailers, etc., and then connect them in the appropriate way. Notice that the dimensions of the "*operations theatre*", the space where the system lies, will be represented in scale to the reality. The user establishes these dimensions when a new model is created. From then on, when the user moves the mouse around this area, he/she will see the dimensions (x, y) in kilometres displayed down at the application's *status bar*.

Next figure (Fig. 3) shows a new Supply Chain represented in the *scMod.exe* window, with 2 suppliers, 2 factories, 2 warehouses and 6 retailers. The retailers supply several customers, and these will be responsible for injecting the demand into the system. Notice that the facilities are connected via *transport paths*, with distances, maximum speeds, road charges, etc., previously configured by means of a property dialog box.

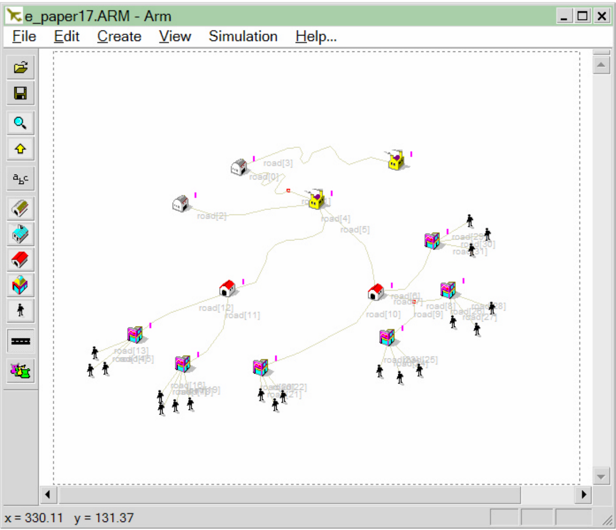


**Fig. 3** A new Supply Chain represented in *scMod.exe.*

Once the Supply Chain network has been represented in the application's window, one must prepare for the implementation of the following steps: (1) <u>define the products available to the system</u>; (2) <u>establish the type of transport paths between each pair of facilities</u>; (3) <u>Create the network nodes</u>; (4) <u>configure each facility to handle its particular products</u>; (5) <u>define the demand at each customer</u>. In the next sections, we will try to explain how these steps can be completed.

As we see, after representing the network much more time will be consumed in carefully and properly configuring the various elements. And this task will get harder with the increase of the Supply Chain complexity and the number of products considered. In each facility (CSU), at least the *ordering policy* specification and the *supplier* specification are needed for <u>each product</u> handled in the facility.

Concerning the *transport paths*, they may also be configured for a specific distance, giving the modeller the ability to "force" certain paths to a convenient distance of travel. This is very useful when certain facilities are located close to each other, but others are not, as for instance, in certain complex Supply Chains including regional and trans-national links, as in the case of ZARA fashion clothes, for example, where some suppliers are located in China, while the main factory and a great number of retailers are located in the Iberian Peninsula.

### 3.1 *Products available to the system*

The products available to the system, or *system products*, can be created and accessed using the button at the bottom of the main toolbar: 

This option, which must be the very first option to use when configuring the Supply Chain, gives access to a *dialog box* (Fig. 4) where the user may name, characterise and link products, sub-products and raw materials, as well as establish among them a kind of *Materials Resource Planning* (MRP) tree, if necessary. The example shown in the figure is purely didactic.

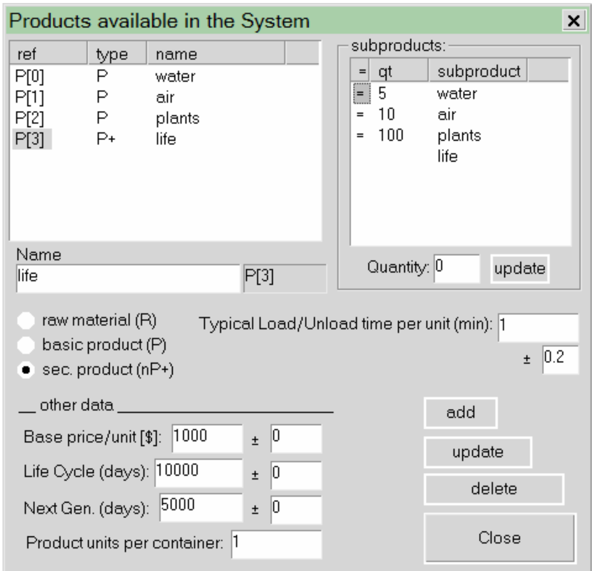


**Fig. 4** Dialog box for creating system products.

Notice that these products may or may not be used by the CSUs, depending on if they are handled or not handled by its inventory. Notice also that in the example of the figure, the secondary product named "*life*", is defined as 5 "*water*" + 10 "*air*" + 100 "*plants*". During the simulation process, this information will be considered invaluable to good stock management.

### 3.2 *Type of transport paths*

After connecting the appropriate CSUs with *transport paths*, these may be configured in order to represent *roadways*, *railways*, *airways*, *seaways*, *information paths* (used to order by catalogue, by telephone, or by Internet), or *xTunnels*, a special kind of path for modelling pipeline-like flows. In addition, some other properties can be configured, like the exact length of the path, the maximum speed allowed, charges, type of charges, etc. Figure 5 shows the *dialog box* where all this can be done.

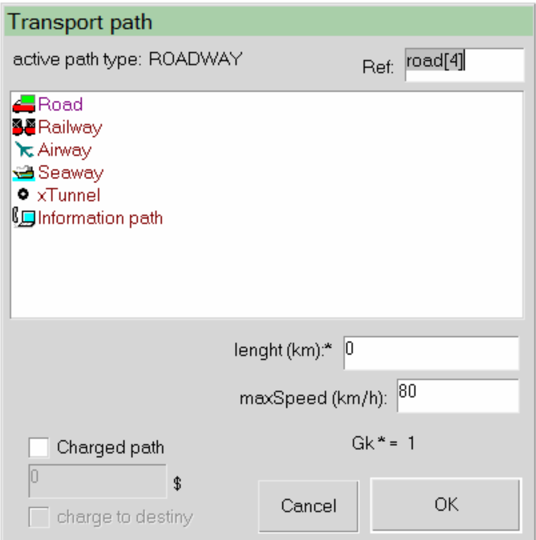


**Fig. 5** Dialog box for creating system products.

### 3.3 *Creating the network nodes*

The network nodes, very important elements for the process of simulation, are automatically created in the application in response to the menu option "*Create->SupplyChainNodes*". This creates the nodes based on the proximity of the endpoints of the various paths, associates paths with nodes and nodes with paths, and establishes links between nodes and CSUs. This ensures that all the elements in the system will be correctly interconnected. Some nodes can then be configured to act as points of pause in the transport network, or even points where the material is transferred from a certain type of vehicle to a vehicle of another kind. This is very useful when modelling interfaces between normal roads and the railway, for example.

### 3.4 *Configure each facility to handle products*

Figure 6 shows the *dialog box* for configuring the products that the CSU will handle in its stock (or inventory), the maximum available space for those items, and their initial stocks. Notice that on the left list of this *dialog box* all the previously created system products are shown, while on the right side list appear only those particular products the CSU handles.

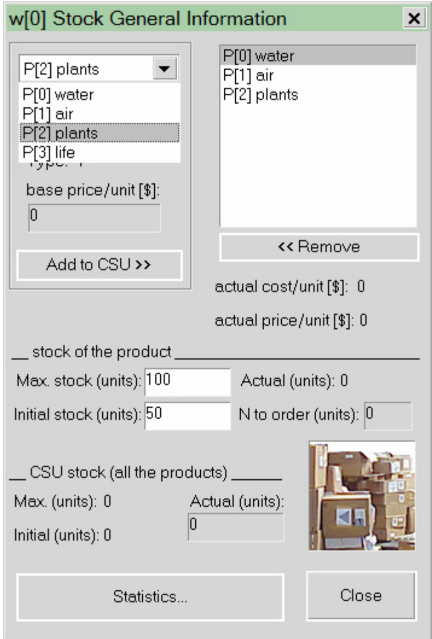


**Fig. 6** Dialog box for configuring the CSU's stock.

The second most important task in the configuration of the CSU products has to do with the choice of the *ordering policy* to be used in each product, and the choice of its *supplier*. This is perhaps the part of the configuration process where the modeller must be more cautious, since small deviations from the appropriate representation of such policies will possibly lead the outputs to significantly diverge from reality. In effect, the choice and the configuration of the inventory model will definitely affect not only the internal dynamics of the CSU, but also the traffic on the transport paths and the pressure on suppliers. In a complex structure of CSUs, such mistakes of modelling may well produce chain reactions where from no reliable conclusions can be obtained. So, it is principally through this *dialog box* (Fig. 7) that each CSU is customized in order to behave the best possible in accordance to the reality.

Notice that for each product handled, there are basically six fields of data to be defined: (1) *when to order*, which identifies the method used in the time domain to define the moment for ordering from the supplier; (2) How much to order, which identifies the method used in the volume domain to compute the amount to order; (3) how to order, specifying if the order is to be sent to the supplier *now* or if it can go at the end of the day with other orders; (4) who to order from, choosing a supplier for the product; (5) cool time, the lead time from the supplier that would be considered 100% appropriate; (6) one order cost, as the cost of ordering from the supplier.

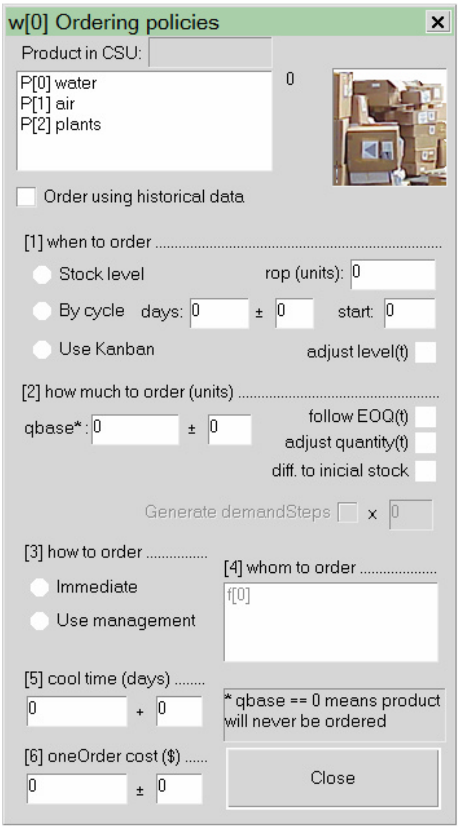


**Fig. 7** Configuring the order policies, the supplier, etc.

A similar *dialog box* is used for *orders of production*, if the facility is to include a production process. Notice, however, that most of these parameters will not be taken into account when using historical data, imported from a text file.

### 3.5 *Defining de demand at each customer*

Since the customer (ultimate customer) is also a CSU, it will be configured in the same manner as any other CSU. Nevertheless, it will not handle any stock resources or production facilities, and it is only allowed either a cyclical ordering of a certain amount of product (see again figure 7, and the *by cycle* option), with the frequency given in days, or, instead, ordering based on historical data. The ultimate customer is, however, an element with which the demand at a certain facility can be made as complex as needed, using several customers to demand different amounts of product at different moments . Each *customer* is also able to generate demand steps, that may be used to help construct the *rigidity matrix* of the Supply Chain, a way for estimating the *flexibility* of the overall structure (see Feliz-Teixeira & Brito, 2004).

## 4. Simulating with *scSim.exe*

The simulator application (*scSim.exe*) looks very similar to the modeller application, apart from the main *toolbar* which now only gives access to some file handling options and to the configuration of the system products. In the menu of the application, the most important option is the "*Simulation*" option, which leads to the simulation start. Notice that the simulation may be set to be *deterministic*, instead of *stochastic*, if the option "*Simulation->UseRandom*" will not be checked. Notice also that a model must have been created previously with *scMod.exe* in order to be opened and simulated with *scSim.exe*, represented in figure 8.

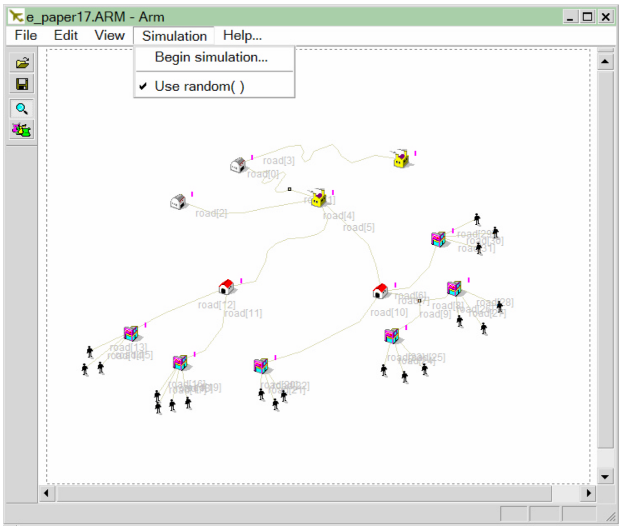


**Fig. 8** A model in the *scSim.exe* application.

When the user chooses the option "*Simulation->BeginSimulation*", another toolbar appears at the bottom of the application's window, from where the simulation process will be controlled (Fig. 9). Most of the options in this toolbar require no explanation, since it resembles a TV controller. That is, once the *"start"* button is pressed, a sequence of actions is started, first testing the consistency of the model, and then connecting and preparing its objects for the simulation process. In the end, the process starts and movement can be seen in the application's window.

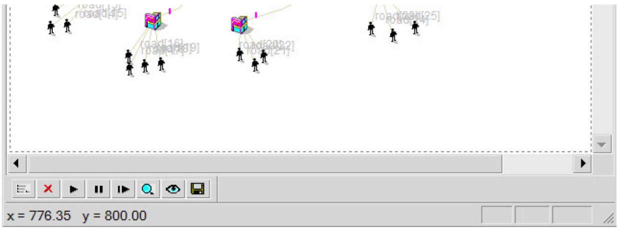


**Fig. 9** The simulation toolbar.

During the simulation process, it is possible to inspect how the important Supply Chain indexes are performing, for example, by simply clicking on a CSU with the *right-mouse-button* and choosing the appropriate option from the menu list that would meanwhile appear (Fig. 10).

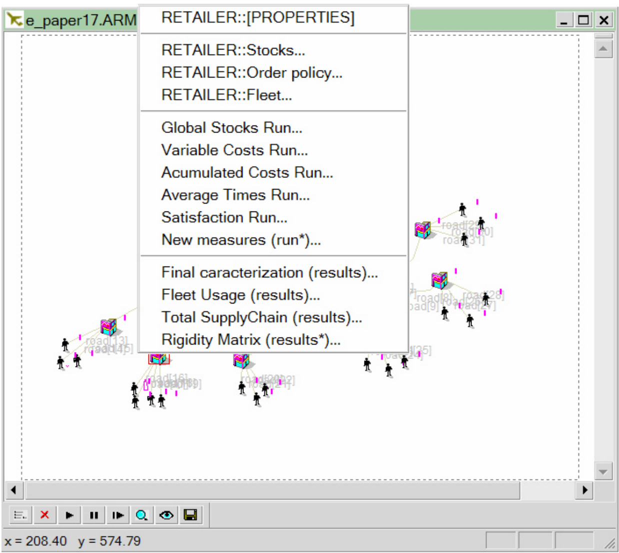


**Fig. 10** Diverse parameters can be inspected during the simulation process, and the conditions reconfigured.

The next figure shows as an example on how the global inventory is performing at the facility *w[0]*.

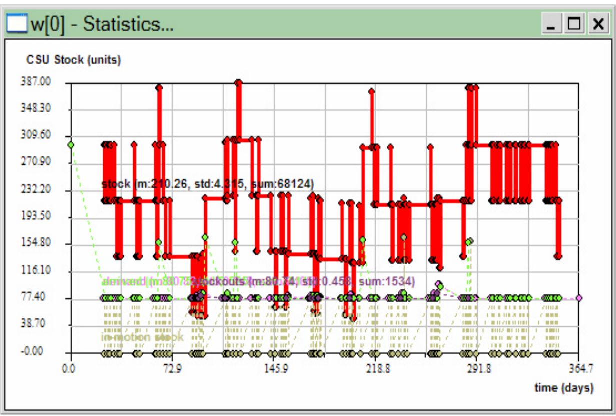


**Fig. 11** A dynamic view of the inventory at *w[0]*.

In addition to these, several other graphics can be visualized even while the simulation is running, providing the analyst with a powerful tool for inspecting the behaviour of its system.

## 5. Metrics and outputs

The outputs of this simulator are firstly focused in a group of relevant operational measures, like the behaviour of the *global inventory* (all items), *variable costs*, *accumulated costs*, *average times*, *satisfaction with suppliers*, etc., with which the analyst may easily estimate the performance of each facility. Then, there is a second group of metrics which are computed from these, raising the analysis to a certain *operational-tactical* level, like the standard measures of *turnover*, *service level*, *stockout ratio*, among others (see Fig. 12). Finally, a tool for helping to measure the *flexibility* of the overall Supply Chain is included, allowing the studying of the network structure as a whole, an important instrument for strategists.

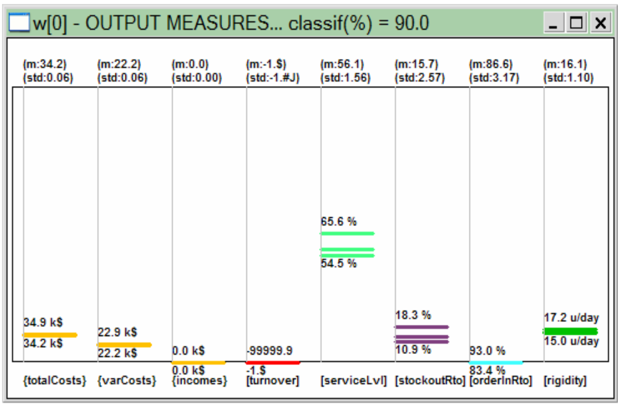


**Fig. 12** Some standard measures[1] related to *w[0]*.

## 6. The rigidity/flexibility matrix

As told before, the simulator includes the ability of helping to compute the *rigidity* of the entire Supply network in the form of a matrix (Fig.13).

[1] In this case the *turnover* was not computed, since no base prices were given to the products.

| | <NO STEPS> | r[0] | r[1] | r[2] | r[3] | r[4] | r[5] |
|---|---|---|---|---|---|---|---|
| s[0] | 10.9 ± 4.3 | f 00 | f 01 | f 02 | f 03 | f 04 | f 05 |
| s[1] | 16.9 ± 7.1 | f 10 | f 11 | f 12 | f 13 | f 14 | f 15 |
| f[2] | 85.9 ± 29.5 | f 20 | f 21 | f 22 | f 23 | f 24 | f 25 |
| w[1] | 45.0 ± 6.6 | f 30 | f 31 | f 32 | f 33 | f 34 | f 35 |
| w[0] | 16.1 ± 2.2 | f 40 | f 41 | f 42 | f 43 | f 44 | f 45 |
| r[0] | 7.5 ± 0.5 | f 50 | f 51 | f 52 | f 53 | f 54 | f 55 |
| r[1] | 9.0 ± 3.0 | f 60 | f 61 | f 62 | f 63 | f 64 | f 65 |
| r[2] | 7.2 ± 0.8 | f 70 | f 71 | f 72 | f 73 | f 74 | f 75 |
| r[3] | 8.9 ± 1.4 | f 80 | f 81 | f 82 | f 83 | f 84 | f 85 |
| r[4] | 7.7 ± 0.4 | f 90 | f 91 | f 92 | f 93 | f 94 | f 95 |
| r[5] | 8.9 ± 1.4 | f 100 | f 101 | f 102 | f 103 | f 104 | f 105 |

**Fig. 13** Matrix of the “residual” *rigidity* of the system.

This matrix is computed by means of generating *steps of demand* at each customer, which introduce a perturbation in the system, and then this perturbation is measured along all the network nodes. At the end of this process, a matrix can be drawn with the results. Notice, however, that only the “residual” rigidity of the system has been measured in the present case, that is, the rigidity exhibited by the facilities without any abnormal perturbation (no-steps). Anyway, from this matrix we may already conclude that the worst rigidity observed was at the factory *f[2]*, exhibiting around 85.9 units/day of stock imbalance.

## 7. Conclusions

The modelling/simulation application presented in this article, specifically devoted to Supply Chain, resulted in a powerful tool for analysis based on an intuitive ambience of interaction with the user. Several unusual tools are included, like the *demand steps* for helping computing the *flexibility* of the overall structure in terms of a *rigidity matrix*, transport paths for modelling *pipeline* type flow of materials, facility related metrics, etc.

The application, made of a modeller *scMod.exe* and a simulator *scSim.exe*, was developed by the author in C++, and is considered a *beta* version academic software. The simulator *scSim.exe*, however, is available as free software, and can be used for directly running and testing models previously created with *scMod.exe*. We invite interested people to try to simulate their own Supply Chain models in this way.

**Authors Biography:**

**J. Manuel Feliz-Teixeira** graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on “Flexible Supply Chain Simulation”.

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Feliz-Teixeira, J. M. (2006). *Flexible Supply Chain Simulation (published thesis)*. Porto, Portugal: Publindustria Publisher.

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Feliz-Teixeira, J. M., & Brito, A. E. S. C. (2004). *On Measuring the Supply Chain Flexibility.* Paper presented at the 2004 European Simulation and Modelling Conference, UNESCO, Paris, France.

# Holistic Metrics Applied to a Practical Supply Chain Study

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KEYWORDS: holistic metrics, simulation, decision making, complex behaviour, practical example, costs, additives, lubricants.

## ABSTRACT

In this article we present a practical example where the concept of *Holistic Metrics* (Feliz-Teixeira & Brito, 2006) is used as a way for sensing the results obtained in a simulation study related to the Portuguese enterprise *GalpEnergia*. Previously described in Feliz-Teixeira & Brito (2005), that case is used again in this article in order to demonstrate the practical value of the *Holistic Metrics* concept. This is basically a simple method for estimating or characterizing the behaviour of *complex systems*, in particular when these are studied throughout simulation. Instead of treating the complex output data obtained from this kind of system along the *time domain*, this perspective encourages analysts to represent such data in the *frequency domain*, somewhat as is adopted in *Fourier Analysis* and in *Quantum Mechanics*.

## 1. Introduction

Currently, there are very few references of practical relevance about reliable metrics for helping in the interpretation of complex systems behaviour. These systems are often based on intricate structures where a high number of entities interact and properties emerge. Even if there are metrics for appropriately characterizing the nodes or individual parts of these structures, measures for the structure as a whole either fail or appear to be too simplistic. Hopp & Spearman (2001, pp.16), for instance, comment on this saying that "*too much emphasis on individual components can lead to a loss of perspective for the overall system*".

The *Holistic Metrics* technique presented here is expected to help surpass this vacuum by giving the analyst a more holistic perspective on the system's behaviour, as well as letting him/her choose almost freely the *complex states* in which such behaviour is to be *projected*. The final hope is that this method will lead to simpler processes in characterizing certain complex systems. For a detailed description of these concepts please refer to Feliz-Teixeira & Brito (2006).

## 2. A short explanation

In our *Holistic Metrics* proposal we represent the overall *system state* ($\psi$) in terms of certain *base functions* ($\psi_i$), and then we only have to find a way to measure the *probabilities* ($\alpha_i$) associated with each of these functions. This can be simply done by means of simulation. An interesting aspect of this method is that each base state function ($\psi_i$) can even be arbitrarily chosen by the analyst, and the probabilities ($\alpha_i$) can most of the time be easily estimated during the simulation through a process of counting. Final results will then be summarised in some expression of the form:

$$\psi = \alpha_1 \psi_1 + \alpha_2 \psi_2 + \dots \alpha_j \psi_j + \dots \alpha_n \psi_n \qquad (1)$$

which could be interpreted as follows: there is a probability of $\alpha_1$ that the system will be found in the state $\psi_1$, a probability of $\alpha_2$ that the system will be found in the state $\psi_2$, etc. This would be the final measure of the system, in a sort of characterization of expectations under certain conditions. This also corresponds to *projecting* the system behaviour into the generalised vectors base of *state functions* ($\psi_i$). The amounts $\alpha_i$ simply correspond to the values of those projections.

Thus, similarly to what happens in *Fourier Analysis*, for example, where signals are to be decomposed into *sine* and *cosine* functions, the time dependent complex behaviour of our complex system will be decomposed into the functions $\psi_i$ and that way moved to the *frequency* domain. A characterization of the system can then be made based on a type of generalised histogram, like the one presented in figure 1:

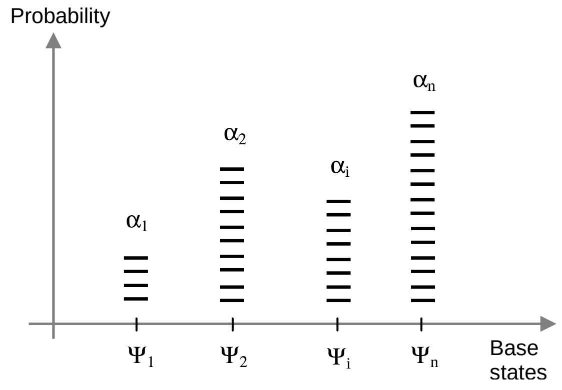



**Fig. 1** Characterization of the system's behaviour

So, once the *base states* are well defined by the analyst, the characterization of the system is possible, no matter how complex the system is. We recall that in many practical cases the analyst is mainly focused on being sure that certain variables of the model do not cross some upper or lower limits, or, if they do, with which probability this happens.

## 3. The case under study

The practical case referred in this article concerns the procurement of additives for lubricants in the oil refinery of Porto, Portugal, and was part of a project of simulation in which we had the intention to help the company *GalpEnergia* decide which purchasing policy to adopt in its Lubricants-Base Plant. As noticed earlier, such a study was published in Feliz-Teixeira & Brito (2005). In it we have basically analysed the supply chain structure presented in figure 2, which was subjected to eight different scenarios of purchasing policies. These policies, in turn, where defined in terms of the minimal amount of materials to order, and analysed based on *purchasing costs*, *holding costs* and *stockout costs*.

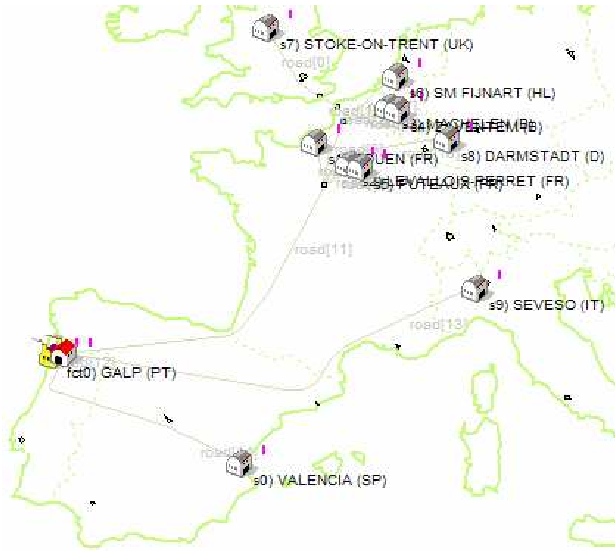



**Fig. 2** The complete Supply Chain under study, with its 10 European suppliers

The results led us to conclude that "*the best approach to operate the plant's warehouse GALP(PT) would be to ensure a <u>fortnightly inspection</u> of its inventory and, once operating with the model ($r_o$, $Q_o$), to set <u>$r_o$</u> as the <u>average demand</u> (in each product) and <u>$Q_o$</u> as the respective expected <u>accumulated demand between supplies</u>, not forgetting to order always at least <u>8% of a truck</u>. This would lead to a total expected savings of around <u>300 K€</u> in one year of operations*".

Such advice has resulted from comparing the following eight scenarios:

1) *hist(30)* – original historical data, model (r=ro, Q(t)).
2) *hist(30)_ss_qq* – historical data, model (r=avrgDem, Q=accDemSuppl)
3) *stat(30)* – statistical data, model (r=ro, Q(t)).
4) *stat(30)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)
5) *stat(15)* – statistical data, model (r=ro, Q(t)).
6) *stat(15)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)
7) *stat(7)* – statistical data, model (r=ro, Q(t)).
8) *stat(7)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)

Notice that the first two scenarios were directly configured with the historical data taken from the plant's database, while the others were driven by statistical versions of such data transformed into a *monthly*, *fortnightly* and *weekly* revision of inventory. All these scenarios have then been simulated and the one with best performances chosen (in the case, scenario 6 = *stat(15)_ss_qq*).

The next figure (Fig. 3) shows how the final costs were changing along these eight scenarios, once focusing the analysis in the *purchasing*, *holding* and *stockout costs*. These values are already those taken from the best truck occupation level, which resulted from various other comparisons within each scenario and was found to be 8% of a truck. We will not consider this aspect in the *Holistic Metrics* analysis, since, for simplicity, we decided to reduce the problem to the choice of the best scenario. The results presented in figure 3 are already corrected by the multiplicative factors with which the demands of all the scenarios have been made equivalent (see Feliz-Teixeira & Brito, 2005).

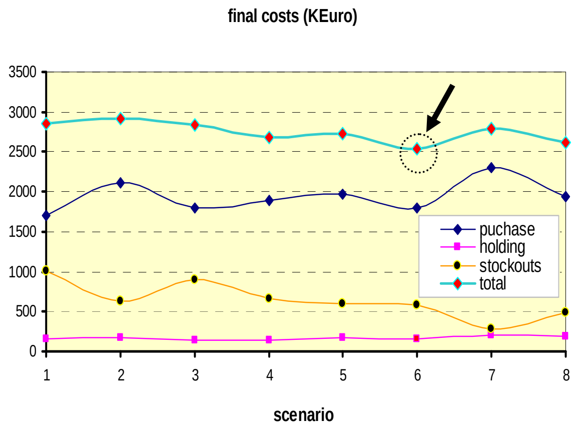



**Fig. 3** Final results, of accumulated costs in a year

As a final remark of this section, one must remind that the previous results were obtained by considering only 108 of the 200 products used in the Lubricants-Base Plant; therefore a more detailed analysis would be necessary to give us a better confidence level on the process of decision.

## 4. Reasoning under *Holistic Metrics*

Management is the science of decisions, therefore in many cases it may almost connect with a certain artistic intuition. In effect, no complex decisions are solely made based on a single criterion, but instead on a weighted equation of criteria which may even contain several solutions. At the ultimate point, it is not infrequent that the manager, as people in their ordinary lives do, has to make a choice from several equal interesting things. This explains the usefulness of certain artistic skills in a manager, skills which are usually seen as intuition for business or simply as a certain ability to predict the future. Although this opinion can be seen as a promotion of *intuition*, it is for sure not in favour of *empiricism*, but instead in favour of good scientific knowledge with which the window of decision can be narrowed, thus transforming scientific knowledge into a tool for the final usage of an intuitive verdict.

*Holistic Metrics*, in a certain way, attempt to bring together such fields, an intuition which will depend on the analyst's sensibility, and the crude rationality of science. As referred to in previous articles, a marriage between Bergson[1] and Kant. So, the figure of the analyst will always be present in this method, and the results will depend on the skills and on the ability that he/she shows on "feeling" the system.

In an attempt to present a practical example, we will analyse again the case of the refinery described in the previous section. We first supposed that the manager was mainly interested in projecting the system's behaviour into 3 complex states related to the *purchasing*, *holding* and *stockout costs*, as in the previous analysis, but then we included one more state related to the *satisfaction* with its suppliers (Feliz-Teixeira, 2006, pp. 69). Later, however, we chose to double this *base* of *vectors* by considering conditions which express not only the *advantages* but also the *disadvantages*. So, in effect we will use 8 *base states*, instead of 4. The behaviour of the system will be projected onto these 8 *base states*.

## 5. Specifying the *base states* ($\psi_i$)

As mentioned in the original article of *Holistic Metrics* (Feliz-Teixeira & Brito, 2006), the *base state functions* (or *base vectors*) can freely be chosen by the analyst in terms of *certain conditions* that must be analysed in the system. In this case, we have considered that the analysis would be mainly focused on the same issues of the previous method, that is, on the *purchasing*, the *holding* and the *stockout costs*. After inspecting the data related to these factors, we could acquire some sensibility for comparing different scenarios, that helped us in choosing the vector's base. The next figure (Fig. 4) intends to help the reader to understand how this

[1] Henry Bergson, a French philosopher from the beginning of the 20th century, who considered time as a history, instead of as an event or as a distance.

can be done. Notice that we have opted for two levels for data comparison: one for those situations considered *advantages* (situations which we will represent by the (+) signal), and another for those considered *disadvantages* (represented by the (-) signal). For instance, in the case of figure 4, any situation in which the accumulated *costs of purchase* lie under the $S_{down}$ level will be considered an *advantage*, while situations where these costs lie over the $S_{up}$ level are considered *disadvantages*.

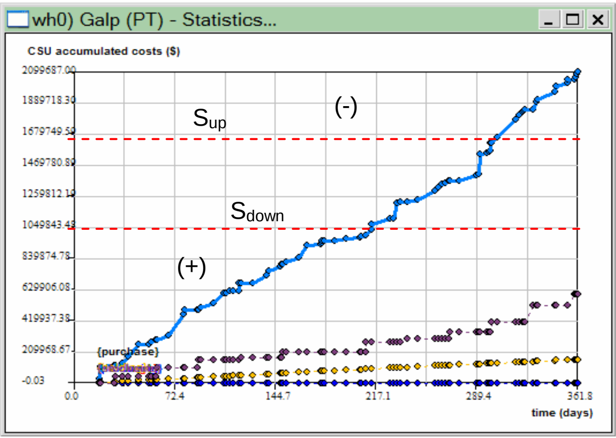



**Fig. 4** Example on how to choose *base vectors*

Notice that the $S_{down}$ and the $S_{up}$ levels can be any, and the best way to choose them will depend on the sensibility and the intentions of the analyst. It is here where Kant starts to meet Bergson. A similar strategy was used for choosing the other *base functions*, which may simply be stated as (notice that these terms will be shown in a short form on the charts):

- Disadvantages:

$\psi_1$ = (-) *accPurchasingCosts > 1650 K€*
$\psi_2$ = (-) *accStokoutsCosts > 960 K€*
$\psi_3$ = (-) *accHoldingCosts > 150 K€*
$\psi_4$ = (-) *satisfSupplier < 90 %*

- Advantages:

$\psi_5$ = *(+) accPurchasingCosts < 1000 K€*
$\psi_6$ = *(+) accStokoutsCosts < 300 K€*
$\psi_7$ = *(+) accHoldingCosts < 50 K€*
$\psi_8$ = *(+) satisfSupplier > 95 %*

## 6. The scenarios finally simulated

As previously said, 8 scenarios have been used in the previous approach in order to search for the "best" solution. Here, we have appended to these, four other scenarios in which the *transportation costs* were considered *null*, in order to have some base for comparisons. So, in the end, the following 12 scenarios have been simulated:

1) *hist(30)* – original historical data, model (r=ro, Q(t)).
2) *hist(30)_ss_qq* – historical data, model (r=avrgDem, Q=accDemSuppl)
3) *stat(30)* – statistical data, model (r=ro, Q(t)).
4) *stat(30)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)
5) *stat(15)* – statistical data, model (r=ro, Q(t)).
6) *stat(15)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)
7) *stat(7)* – statistical data, model (r=ro, Q(t)).
8) *stat(7)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)

9) *hist(30)_zero* – original historical data, null transportation costs.
10) *stat(30)_zero* – historical data, null transportation costs.
11) *stat(15)_zero* – statistical data, null transportation costs.
12) *stat(7)_zero* – statistical data, null transportation costs.

To the simulator application was added the ability for counting the occurrences of the appropriate conditions, in order to compute an estimation of the probabilities $\alpha_i$ corresponding to the various $\psi_i$. Each scenario was simulated independently, and the data resulting from it recorded in two general tables.

## 7. Results and discussion

The simulator used in this study was developed by Feliz-Teixeira during his doctoral work, and it was specifically conceived for supply chain modelling and simulation[2]. With it, each scenario was simulated during one year of operation. Then, the output data was analysed using the *Holistic Metrics* tool included in it, and the final tables of results were created. Table 1 refers to the situations of *disadvantages*:

| | (-) purchase > 1650 k€ | (-) stockouts > 960 k€ | (-) holding > 150 k€ | (-) satisf < 90% |
|---|---|---|---|---|
| hist(30)_zero | 0.00 | 6.31 | 8.74 | 3.53 |
| hist(30) | 6.47 | 6.31 | 8.74 | 4.71 |
| hist(30)_ss_qq | 18.16 | 0.00 | 9.17 | 2.70 |
| stat(30)_zero | 7.36 | 0.00 | 0.00 | 3.16 |
| stat(30) | 8.25 | 0.00 | 0.00 | 3.16 |
| stat(30)_ss_qq | 24.37 | 0.00 | 0.00 | 3.75 |
| stat(15)_zero | 7.06 | 0.00 | 2.92 | 3.91 |
| stat(15) | 7.81 | 0.00 | 2.92 | 3.91 |
| stat(15)_ss_qq | 0.00 | 0.00 | 0.00 | 2.70 |
| stat(7)_zero | 2.12 | 0.00 | 2.13 | 2.87 |
| stat(7) | 7.98 | 0.00 | 2.13 | 2.87 |
| stat(7)_ss_qq | 0.00 | 0.00 | 0.00 | 1.35 |
| | % | % | % | % |

**Table 1** Results for the conditions of *disadvantages*

[2] See http://www.fe.up.pt/~feliz/supplychainsimulator.htm

A similar table for the conditions of *advantages* has also been created:

| | (+) purchase < 1000 k€ | (+) stockouts < 300 k€ | (+) holding < 50 k€ | (+) satisf > 95% |
|---|---|---|---|---|
| hist(30)_zero | 64.24 | 17.80 | 24.76 | 88.24 |
| hist(30) | 62.78 | 17.80 | 24.76 | 85.88 |
| hist(30)_ss_qq | 45.52 | 55.69 | 22.75 | 87.84 |
| stat(30)_zero | 60.15 | 33.12 | 38.45 | 90.53 |
| stat(30) | 60.15 | 33.12 | 38.45 | 87.37 |
| stat(30)_ss_qq | 49.67 | 35.57 | 27.53 | 83.75 |
| stat(15)_zero | 62.47 | 38.29 | 33.87 | 82.03 |
| stat(15) | 62.46 | 38.29 | 33.87 | 81.25 |
| stat(15)_ss_qq | 67.59 | 64.58 | 31.02 | 83.78 |
| stat(7)_zero | 62.94 | 100.00 | 32.27 | 81.03 |
| stat(7) | 60.99 | 100.00 | 32.27 | 82.18 |
| stat(7)_ss_qq | 74.63 | 76.76 | 34.38 | 87.84 |
| | % | % | % | % |

**Table 2** Results for the conditions of *advantages*

Finally, by organizing this data in the form of the appropriate graph, one gets to the final tool from which decisions can be made, that is, to what we may call the *Holistic Metrics Chart*, which in effect corresponds to the *spectrum* concept of *Fourier Analysis* or to the graph of *observable states* of *Quantum Mechanics*. As we will soon notice, from now on decisions will tend to request the help of a certain intuition, and that is where Bergson starts to surpass Kant.

The next chart represents the projections of those conditions considered *disadvantages*:

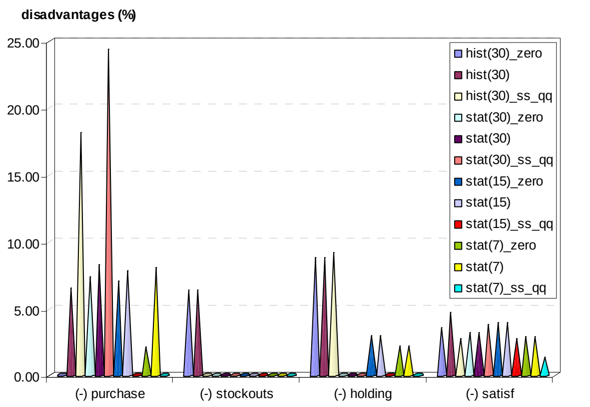



**Fig. 5** Holistic Metrics Chart with the final projections for the *disadvantages*

As we can see by inspecting this chart, some scenarios could simply be rejected if the analyst's intention would be the simple minimising of disadvantages. In effect, scenario *stat(30)_ss_qq* shows the highest disadvantage projection in the *purchase* "direction", therefore we could simply reject it. Anyhow, wisdom would perhaps tell the analyst not to pursue this initial impulse, because the same scenario could probably also show a large projection in the *advantages* chart. Actually, that is not the case, as one can see by inspecting the *advantages* chart shown in figure 6, and so the rejection of this scenario could be considered a good decision.

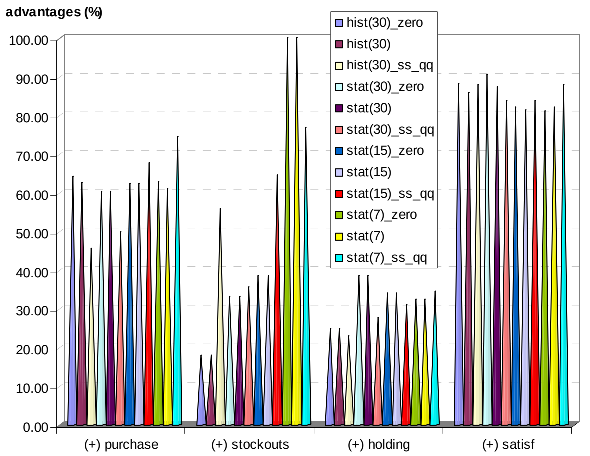
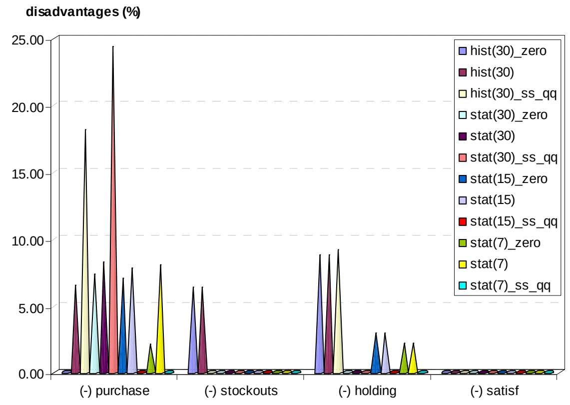



**Fig. 6** Final holistic projections for the *advantages*

Even if it seems much easier to make decisions in the *disadvantages* chart, it is important to notice that this will depend on the choice of the various $S_{up}$ and $S_{down}$ levels for the definition of the *base vectors*. In respect to the vector *(-)stockouts* of the *disadvantages* chart (Fig. 5), for instance, we can see that it is perhaps not the best suitable for allowing us to compare the various scenarios, since many of the projections are in effect null. This base vector was chosen to be *accStokoutsCosts > 960 K€*, and so we would recommend that the analyst try a lower value in this condition, like, for instance, *700 K€*.

On the other hand, by inspecting the *advantages* holistic chart (Fig. 6), we can see that in certain "directions" the various scenarios behave with little disparity, meaning that decisions in fact have to be taken based on the analyst's instinct. In a first phase of our analysis, for example, one can even decide to remove certain of those vectors if we observe that their contribution to decision is low. In effect, *(+)purchase* and *(+)satisf* can be ignored on the *advantages* holistic chart, while the *(-)satif* can be ignored on the *disadvantages* chart. In doing so, we would stay with the following data in order to enter the next level of decision:



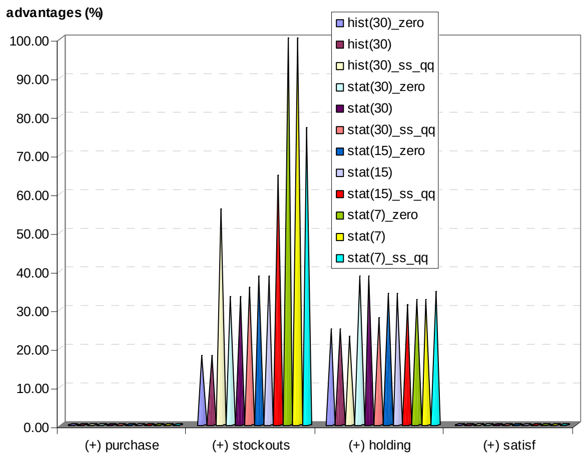




**Fig. 7** Holistic data after rejecting certain vectors

From this we can see that, by working a little more in this process, it would not be difficult to reach the situation of making a choice based on the best performances concerning *stockouts*, naturally focusing the attention on scenarios *stat(15)_ss_qq*, *stat(7)* and *stat(7)_ss_qq*, as they are the most prominent. This means that slowly the analyst would probably be led to the same decision reached with the previous method, which was the scenario *stat(15)_ss_qq*. Notice that scenario *stat(7)_zero* is just hypothetical, so it may not be considered an option.

## 8. Conclusions

We have presented a practical and didactical example on using *Holistic Metrics* to analyse the behaviour of a real system. This is a method in which the analyst is encouraged to exploit his/her intuition during the strategy of approaching a final decision, even if all the measures in the process are in effect quantitative. The case taken as an example has also been analysed in a previous article by means of a standard method. By roughly comparing both processes, we were led to believe that, in the end, *Holistic Metrics* would probably lead to the same conclusions. However, a final choice of the best scenario was not obviously made, in this case, since it would depend on the analyst's feeling and because that was not the major objective of the article. We hope, however, that at least the reader could feel encouraged to finish such reasoning, and exercise intuition in order to finally get to a good choice.

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**J. Manuel Feliz-Teixeira** graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on "Flexible Supply Chain Simulation".

**António E. S. Carvalho Brito** graduated and received MSc in engineering from the Faculty of Engineering of University of Porto and PhD in Simulation from the Management Department of University of Cranfield (UK). He teaches at the university since 1981 on the subjects of simulation, programming and systems information.

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# Bicycle Wheel: A Surprising Wind Turbine

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KEYWORDS: Renewable energy, wind power, "convergent" turbines, moment of inertia, angular momentum, mechanical accumulator, inexpensive solutions.

**ABSTRACT**

This is the third in a series of articles about the concept of *convergence* in turbines (Feliz-Teixeira, 2006b), in particular in those used for wind power capture. Herein we present a discussion and some conclusions about the design of the bicycle wheel converted into an easy-to-assemble *convergent* wind turbine. The results observed in practice have been so promising that we suggest that this could be an excellent design for a wind turbine. We also expect once more to promote renewable energies so that they definitely become a strong alternative to generate electrical power. A short video of a small bicycle wheel running with wind can be seen at http://www.fe.up.pt/~feliz.

## 1. Introduction[1]

Actual wind systems are of diverse kinds, but most of those dedicated to generate electrical power are of the *divergent* type. As alleged in Feliz-Teixeira (2006b), these systems tend to enlarge the flow of the wind, therefore introducing not only a reduction in the wind speed but also a certain dispersion at the system's boundaries. Due to the tendency for moving the wind flow from the central region to the peripheral zones, and also due to the blades' design and the expensive technology used, these systems are suspected to be less efficient and much more expensive than certain easy-to-build *convergent* ones. On the contrary, *convergent* turbines seem to concentrate the flow instead of dispersing it, therefore avoiding some of the effects that contribute to reducing the efficiency of the system. These systems have a transparent central spot where the wind can pass freely, and that is believed to create a low pressure responsible for sucking the peripheral wind to this central zone. This is also believed to contribute to a higher efficiency than expected in the usual turbines.

In the last two articles, discussions have been carried on regarding the design of some *convergent* systems, for single and double turbines (Feliz-Teixeira, 2006a), and the advantages and challenges that they imply. But, in neither case was the issue of accumulating the wind energy addressed, as the problem of finding a more efficient response to the wind flow was also not addressed, since standard turbines start to run only around 8 *Km/h*, and therefore a substantial amount of energy is simply lost on days of low wind. It is, somehow, intriguing for most people that huge machines installed along certain mountains spend most of their time stopped. We obviously understand that the power contained in low winds is very small, but if we calculate the energy lost on some of those days or even weeks it is our belief that this energy is also of value. A simple calculation shows, for example, that a single day of a stopped 8 metres radius turbine (with 30% of efficiency) while the wind continuously blows at 5 *Km/h* (=1,4 *m/s*) would represent less 2,4 KWh of energy injected into the public network: 300 Watt x (30%) = 100 Watt during 24 hours = 2,4 KWh. That is, less 48 lamps of 100 Watt operating in the illumination of the streets, almost the illumination of a small village. That is, less 96 laptop computers

[1] We would like to state that any novel ideas presented in this article are to be considered anti-patent, that is, they are offered to the public domain by its author and anyone may implement them freely without the need for any special permission, other than a symbolic contribution in order to cover the author rights. Please contact the author in this case.

operating during a day of work, in a medium size enterprise. If one thinks of 100 stopped turbines, then we think of 100 villages without public lighting or 100 medium size enterprises with their laptops off, for instance. We have considered a single day. It is not rare, however, to see those turbines stopped for a week, or even more.

In this article we will not only present a way of converting the bicycle wheel design into an efficient *convergent* wind turbine, but also discuss the idea of accumulating the wind energy in a mechanical form, in the wheel itself, and what such a move would imply in terms of efficiency in the overall process of energy production. Some systems based on the bicycle wheel design are also offered as interesting ways of collecting the energy from the wind.

## 2. Bicycle wheel, the perfect design?

Apart from all the fascination drawn by wheels, which have since for ever attracted the attention of a large number of the curious, inventors, mysticists and scientists, it is in fact a sort of magic to appreciate a bicycle wheel running “alone” by means of the wind. Frequently, as we have good knowledge of the weight and the dimensions of such an element, we find ourselves asking the question: how is that possible, to run so fast with almost no wind? The answer lies in two aspects: the *convergent* design which lets the turbine start running at low wind speeds; and the ability of accumulating energy in a mechanical form, in the wheel itself. We will firstly talk about the first aspect.

Any attentive observation of the structure of a bicycle wheel will bring light to our spirits: in effect, the steel wires connecting the metalic ring to the central axis of rotation are mounted in a way that resemble the *convergent* turbine design. In the centre, these tense wires are inserted almost parallel to the direction of the wind flow (perpendicular to the plan of the wheel), while they gently turn around as they approach the periphery, where they finally become practically perpendicular to the wind flow (see Fig. 1). This is practically the same design as the one proposed in the previous two articles concerning this subject. This is, therefore, a very nice coincidence, which have brought lots of joy to our experiments. So, to convert this system into a turbine one only needs to construct the blades, that is, to tightly wrap some TESA® adhesive tape, a surprising resistant and extremely light material, around the appropriate wires:

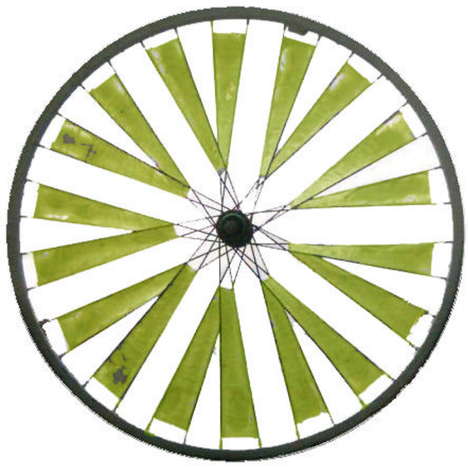

**Fig. 1** Bicycle wheel converted into a *convergent* turbine.

Figure 1 shows a real turbine made with this simple technique. Notice the obvious transparency of the central spot, and the area of exposure of the blades increasing towards the periphery, in order to take the advantage of a superior torque. The wind is thought to slide down the blades in the direction of the central transparent spot due to the low pressure produced in this zone. The radius of a normal bicycle wheel is around 0,27 metres, and so one expects such a system to be exposed to around 1,9 x 0,073 x 2,744 = 0,4 Watt (5 Km/h) and 1,9 x 0,073 x 1000 = 139 Watt (35 Km/h). Thus, commercially this would easily be considered a system of near 100 Watts, that is, enough to feed two laptops.

Considering $P_0$ the power spent on the forces of friction affecting the overall structure, including the air and even the inertia of a possible generator, one can say that the wheel will start to turn when the overall torque per unit of time ($P_w$) induced in its blades surpasses $P_0$ , that is:

$P_w > P_0$ => wheel starts to turn

For a certain $P_0$, this of course will mostly depend on the blade design and on the radius of the wheel. So, in principle it will not be difficult to build one of these turbines to turn with a very low wind, since the process of construction allows it to be extremely light and the blade design captures the superior torque near the system boundaries. The rate by which the wheel approaches the final speed will obviously depend on the difference between $P_w$ and $P_0$, since this is the power transferred into movement: ($P_w - P_0$ ). For this to be acheived in practice, the wheel must be perfectly calibrated, of course.

The metalic ring around the blades will increase the overall weight of the turbine, and therefore it will also contribute to the increase of $P_0$, but even so, it does not interfere too much with the system's ability to start rotating, any more than slowing a bit the process. On the other hand, this ring will be a good accumulator of rotational energy, as we will see soon. We may for now consider that the change in *angular speed* ($w$) induced by the wind *force* ($F_w$) in the turbine comes from the simple fact that *torque* ($t$) is what changes *angular momentum* ($L$):

$$t = dL / dt = I \, dw / dt \qquad (1)$$

where $I$ is the *moment of inertia* of the turbine, which is dependent on the design and on the mass. From this we can write:

$$dw = ( t / I ) \, dt \qquad (2)$$

Now, since it holds:

$t_w = F_w \times b =$ wind force x distance of action = wind torque

$t_0 = F_0 \times e =$ resistive forces x distance of action = anti torque

We easily deduce that the new angular speed ($w$) induced by these two torque contributions at the instant of time $t+dt$ is:

$$w(t+dt) = w(t) + ( F_w \, b / I ) \, dt - ( F_0 \, e / I ) \, dt \qquad (3)$$

Notice that the factor ($F_0 \, e$) is used here as a simplistic approximation for the resistive forces involved, and must be considered null when the turbine is not rotating ($w = 0$). Otherwise, the turbine would start to move in the opposite direction if stopped. The overall expression shows, however, that for a certain level of torque, a turbine with higher *moment of inertia* will tend to respond slower. A mass located far from the centre increases the moment of inertia, for example, but the system will always start to rotate as long as it holds $t_w > t_0$. Notice also that even if the two forces $F_w$ and $F_0$ would be comparable, the fact is that usually one has $b >> e$, since most of the resistive forces concentrate near the centre, and therefore the contribution of the wind force for the rotation is more superior than the contributions of the resistive forces for the "anti-rotation". So, the *convergent* design is also an important factor for minimizing the effect of resistive forces, since it tends to capture the wind torque far from the centre ($b$ large).

## 3. A mechanical accumulator of energy

Accumulating the energy from a renewable source with the uncertainty of the wind or of the solar radiation is usually a challenge, and thus good management of the energy inventory is essential. Usually, large wind systems are prepared to inject the generated electrical power directly into the public network, but smaller systems are frequently connected to banks of batteries where the energy is accumulated before usage, in order to prevent shortages and ensure a steady output. The battery, however, acts as a capacitor, and therefore also as a *low-pass* filter for the electrical signal produced by the generator, as shown in figure 2:

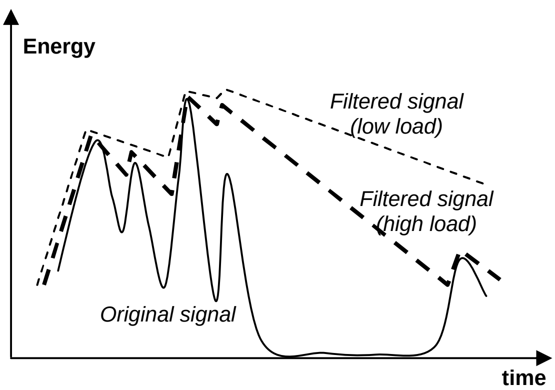


**Fig. 2** The effect of a capacitor in an electrical signal.

Notice that in principle the battery works as a capacitor and so the output level is more stable than the original signal. Such stability depends, however, on the *load* the system is supporting in a given moment. With no external load or at low level loads the stability is high, of course, but it tends to deteriorate for higher rates of consumption of energy (=high loads). The only way of avoiding such a problem is either capturing more energy or consuming less energy, obviously.

But we may now recall that the relation between *angular speeed* ($w$) and *angular momentum* ($L$) is:

$$L = I\, w \tag{4}$$

So, looking with attention to equation 3 and multiplying its two members by the *moment of inertia* ($I$) leads us to the following equation for the increment of *angular momentum*:

$$L\,(t+dt) = I\, w(t) + F_w\, b\, dt - F_0\, e\, dt \tag{5}$$

As we know, *angular momentum* is conserved in the absence of external torque acting in the system, and this equation can therefore also be seen as an accumulator, in which the term $(F_w\; b\; -\; F_0\; e)$ contributes to the increase in accumulated energy, and ($F_0$ $e$) represents its natural decline due to the overall resistive forces, including the generator's resistance. The energy accumulated is of course proportional to $Iw(t)$, meaning that wheels with a higher moment of inertia will accumulate more energy, and, once the situation $b >> e$ is maintained, the wheel will easily be found running "alone" even after the wind has vanished. That is due to the energy in the mean time accumulated in the form of *angular momentum*. With a certain humor, we may proudly say that this is a wind turbine which can even run without wind.

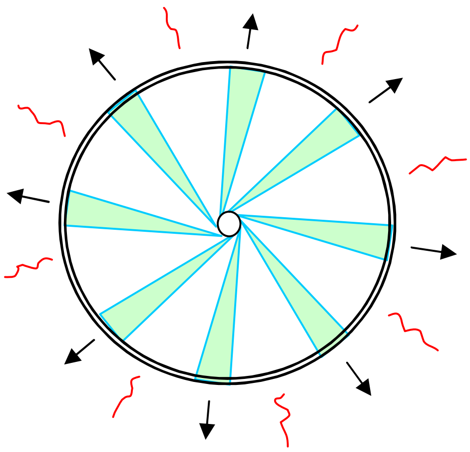

**Fig. 3** The energy accumulated in the form of tension due to the centrifugal forces.

In the absence of the wind force, the small torque from resistive forces is what will try to stop the wheel. The energy is, in effect, for a while kept prisoner of a sort of virtual gravitational field parallel to the plan of the wheel, which is created by centrifugal forces. Thus, a larger ring's mass implies that the system "sees" the resistive forces *less*, and so it approaches the ideal situation, which, of course, would imply the continuous motion. Notice, however, that the accumulation of energy by this method is limited to the resistance of the materials employed. Beyond that, the wheel would simply disintegrate. Figure 4 shows how one of these wind turbines could look when mounted on an American mill structure.

**Fig. 4** Bicycle wheel turbine mounted on a typical American mill structure. With 2 m of radius, this would receive 8 KWatt of wind power at 10 m/s wind speed.

## 4. Angular speed

The previous discussion was mainly about the sensibility of the bicycle wheel related to turning, therefore we talked of the *rate of change* of angular speed. Even if some conclusions could be achieved, nothing was deduced about the *angular speed* itself, under a certain wind regime. Instead of the angular momentum conservation law, we will now make use of the law of conservation of energy. In this case, we may state it by saying that the *total torque* equals the change in *kinetic energy*:

$$t_w - t_0 = ½\, I\, w^2 \tag{6}$$

From where one gets, during a time $Dt$:

$$(P_w - P_0)\, Dt = ½\, I\, w^2 \tag{7}$$

And finally:

$$w = [\,2\,(\,P_w - P_0\,)\,Dt\,/\,I\,]^{½} \tag{8}$$

So, if the wind blows in a continuous regimen with power $P_w$ , and if $P_0$ = ½ $P_w$ meaning the efficiency of the system is 50%, then, for a bicycle wheel of 2 m radius, mass of 5 Kg, and a wind power of 8 KWatt, the *angular speed* of the wheel will increase with the time by means of the relation (notice that $I = m\ r^2$ is the moment of inertia of a ring):

$$w = [\ 2 \times 0{,}5 \times 8000 \times Dt\ /\ (5 \times 4)]^{½} = 20{,}0 \times Dt^{½}$$

And, for instance, 9 seconds after starting we would have:

$w$ = 20,0 x 3 = 60,0 rad/s
f = $w$ / (2π) = 9,55 Hz = 573 rpm

The generator would therefore be producing 4KWatt at 573 rpm. The next graph shows how the *angular speed* (rpm) would tend to increase with time, if no increase of the resistive forces with angular speed would be considered.

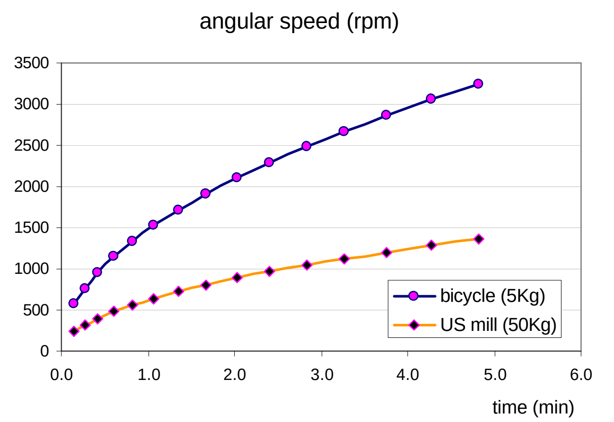


**Fig. 5** Ideal angular speed responses for a bicycle wheel of 5Kg, 2 m radius, and an equivalent American windmill of 50Kg, when receiving a constant power of 8 KWatt, with efficiency of 50%.

Obviously, a windmill would perform better if of the same weight, but in effect the weight of an American windmill of 2 metres radius is not 5 Kg. It can be around 10 times that (50 kg), at least, if we make an estimation with an average density of 5000 kg/m$^3$ for the metalic material used in its blades. This obviously dictates an advantage for the bicycle wheel. We must be aware, however, that the previous graph does not take into account the increase of the resistive forces with the increase of rotational speed, due to drag effects and also due to the increase in air friction at tip speeds approaching the speed of the propagation of sound (*match-I*). At these speeds, air becomes incompressible, and so it acts as if approaching the solid state, therefore introducing a high resistance against the movement. In the case of the previous turbine, *match-I* would be reached at around 1600 rmp. At this speed, the turbine tips would be moving with a velocity of 340 m/s = 1224 Km/h, much faster than a commercial airplane! Thus, what is usually acceptable is that the system will not surpass a tip speed of around 100 m/s, which, in this case, corresponds to:

v = ω r = 2π f x 2 = 100 m/s
f = 100/(4π) = 7,96 Hz = 478 rpm

We may therefore conclude that we can build a bicycle wheel turbine much lighter than an American windmill, yet with an interesting moment of inertia giving it the capacity for accumulating energy. The advantages are mainly in the increase of rotational speed, and the ability of helping to accumulate energy, and therefore it may be used for electrical generation too. Figure 6 shows the common American windmill, used for water pumping, but certainly not for generating electrical energy due to its low rotational speed.

**Fig. 6** A typical American windmill style turbine, installed somewhere in China.

## 5. Some images and some comments

Here we will consider some other aspects related to these convergent turbines, mainly involving the design, ways of implementation and curiousities.

We may start by stating that, in our point of view, the American wind mill turbine suffers from two small problems: excessive weight due to the large quantity of metal used in its blades, and a subtle problem of design, which does not let the turbine take advantage of a truly *convergent* system. A good observer will detect such a design failure while inspecting figure 7:

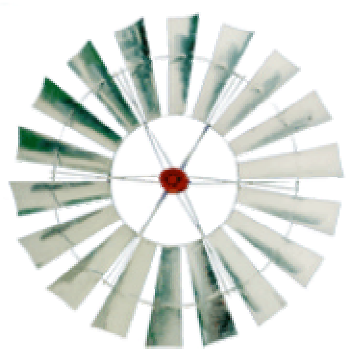

**Fig. 7** The American windmill turbine, slightly different from the proposed convergent design.

Another image we show here (Fig. 8) is of a normal bicycle wheel transformed into a turbine and simply mounted to a tree, which rotates with extremely low winds. People may try to make this experiment and notice that sometimes the wheel is running so much that it seems almost impossible, or like something magical.

**Fig. 8** A bicycle wheel fixed to a tree runs with extremely low wind speeds.

The next image (Fig. 9) is a montage with which we expect to help the reader to imagine how a small-medium generator installed in a little cottage could look. Notice that a turbine constructed based on a bicycle wheel structure can be made very light and is very easy to install. This will also make the support structure much simpler. Besides, the outside aluminium (or other light material) ring may be thought of as a protection against hazards. If there is an accident, the results will probably be less significant, at least compared with the hazards due to a normal turbine with its strong and solid blades.

**Fig. 9** A probable view of a wind system, mounted to supply electricity to a small house.

Another simple way of capturing the wind for generating electricity is the scheme shown in figure 10. The advantage of this is that the structure can be made of standard bicycle wheels, which are easy to obtain. Notice, however, that the resistive forces are now acting also at significant distances from the axis of rotation, meaning that the system is in principle less efficient. This may of course be improved. Notice also that another way to connect the wheels is using little skate wheels between the bicycle ones, so that the turbines would rotate all to the same side. This scheme could even be mounted at the top of certain buildings, or on a farm in the form of an extensive wall which naturally captures the wind energy.

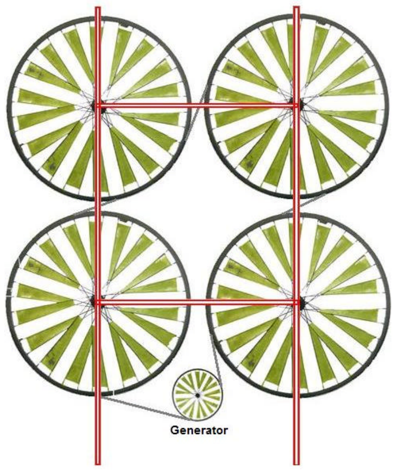


**Fig. 10** Another scheme using normal bicycle wheels for producing electricity.

In figure 11, one shows two possible quasi-static systems based on *convergent* turbines, which would simply adapt their positions by means of a computer controlled base structure.

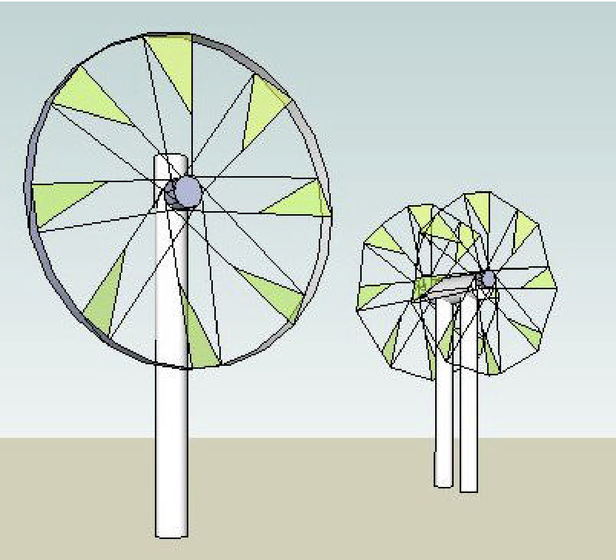

**Fig. 11** Examples of two quasi-static *convergent* systems, with single and double turbines.

Finally, in figure 12 several types of double wind convergent systems are shown, some of which make use of the previous idea of a ring for accumulating energy. In effect, a variety of these systems can be installed for producing electrical energy.

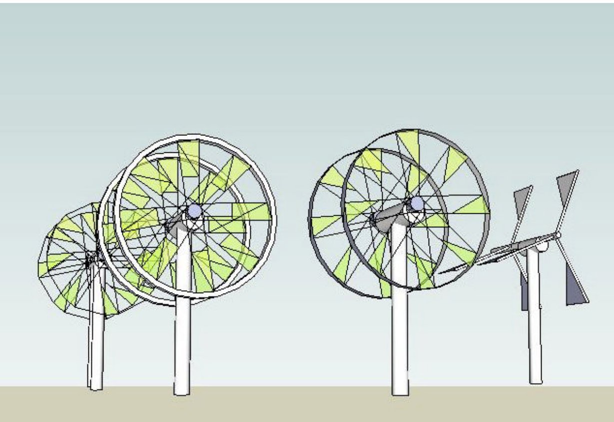

**Fig. 12** Several types of wind systems taking advantages of rings and of double convergent turbines.

## 6. Conclusions

After having built and appreciated several wind turbines made from standard bicycle wheels, we believe that this is a good and simple design that can also be used in larger wind turbines, even in those dedicated to generating electrical power. The low weight of the turbine achieved with such a method will lead the system to be able to rotate at significant speeds, and the ring around it will mainly contribute to the accumulation of the energy not directly transformed by the generator into electrical power. So, we not only believe that this design is interesting for constructing efficient systems, but also that such systems will not be as demanding in terms of battery stability as the present ones. Besides, we consider the design quite beautiful and easy to adapt to several different circumstances.

**Author Biography:**

**J. Manuel Feliz-Teixeira** graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and received an MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on "Flexible Supply Chain Simulation".

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Feliz-Teixeira, J. M. (2006b). Low-cost Convergent Turbine for Wind Power Usage. *Online publication at http://www.fe.up.pt/~feliz* (Registred with the Portuguese Society of Authors).

Wikipedia. (2006). *Wind turbine*. Wikipedia, the free encyclopedia. Retrieved November 2006, from www.wikipedia.org

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# Double Convergent Wind Turbine: To Follow the Wind Direction

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KEYWORDS: Renewable energy, wind power, "convergent" and "divergent" turbines, wind tracking systems, inexpensive solutions.

## ABSTRACT

In a previous article we have introduced the concepts of "divergent" and "convergent" turbines (Feliz-Teixeira, 2006), and proposed a wider usage of the idea of "convergence" in wind systems. Here we present a double turbine for wind power capture which uses precisely this concept and naturally has the ability of aligning itself with the direction of the wind flow. Although the model presented here is an experimental prototype, it has been observed that it operates with very promising performances. In this article we show the turbines' structure and present a first model of a rotor a metre in diameter. One may get a better idea of how this system performs by watching two short videos at http://www.fe.up.pt/~feliz.

## 1. **Introduction**[1]

For centuries wind energy was used in the fields of transportation (sailing) and water pumping and grain grinding (mills), but since the last century it is also being used for electrical power generation (D.W.I.A., 2003), and, even if indirectly, for flying (in effect, airplanes fly due to the wind invoked when running at high speeds). In the last decades, however, with the development of new materials and the increase in generators' efficiency, and also due to the strong applause coming from a large and growing number of citizens arguing for cleanness and renewable, wind energy traversed from an initial period of uncertainty to a kind of modern trend. In each international oil crises, like in the *Iranian Revolution* (eighties) and more recently the Anglo-American *Iraq Invasion*, a generalised interest in renewable energies could also be observed, not only due to the economical advantages of such a move, but, as we said, also due to the development of a superior consciousness in the populations about the finitude of Earth resources. Renewable energies are therefore no longer merely a simple possibility, but they have become an approach to living, a philosophy of existing. In effect, although under the strong pressure of the crazy-consumption-style promoted by certain wealthy companies, populations seem to become more interested not only in using non-destructive processes for producing energy, but also in reducing the excessive consumption which have been installed in most of our societies, mainly in the West, during the last century's excitement age. "*The Earth is a finite system*", Lehoucq (2005) argues in a wise article regarding present energetic resources versus demand figures. Understanding the importance of opting for a renewable process shows, in particular concerning energy production, and in our opinion, an evolution to a superior mindset. After all, we may not forget that *Life* includes humans, and not the opposite, humanity being only a small part of overall existence. But another aspect to take into account is the climate change, which is right there in front our eyes, ready either to be understood or to be ignored, depending on our wisdom, of course.

The system presented in this article, in its almost

[1] We would like to state that any novel ideas presented in this article are to be considered anti-patent, that is, they are offered to the public domain by its author and anyone may implement them freely without the need for any special permission, other than a symbolic contribution in order to cover the author rights. Please contact the author, in this case.

naive simplicity, aims to contribute to the spreading of such a non-destructive-renewable-energy frame of mind, particularly concerning energy production. Throughout such a system, one may also wonder why one often get the impression that simple and inexpensive solutions are still ignored, while expensive systems systematically win the race. Could it make any sense that at a certain point energy *must not get cheaper*?

## 2. Divergent and convergent turbines

Most of the wind turbines currently in use are of the type we consider "*divergent*" (Feliz-Teixeira, 2006). A *divergent* turbine, schematically shown in figure 1, is considered a system which tends to enlarge the flow of the wind, therefore introducing not only a reduction in the wind speed but also a certain dispersion at the system's boundaries. Due to the tendency for moving the wind flow from the central region to the peripheral zones, and also due to the blades' design and the expensive technology used, these systems are alleged to be less efficient and much more expensive than certain easy-to-build *convergent* ones.

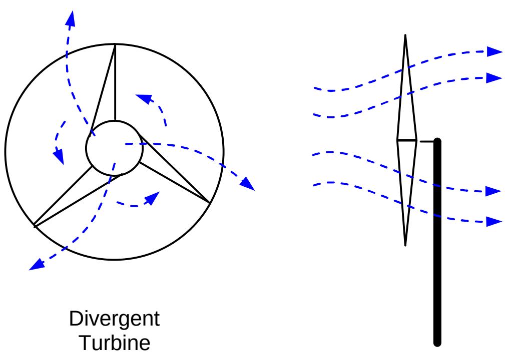


**Fig. 1** Expected lines of force induced in the flow in a *divergent* turbine running to the left. Frontal and lateral views.

On the other hand, in *convergent* turbines, depicted in figure 2, we expect the wind behaviour to be substantially different, concentrating the flow instead of dispersing it, and therefore avoiding some of the effects that contribute to reducing the efficiency of the system. Besides, these systems have a transparent central spot where the wind can pass freely. It is believed that this will probably create a central low pressure which is responsible for sucking the peripheral wind to this central zone. And that is also believed to contribute to a higher efficiency than expected in usual turbines.

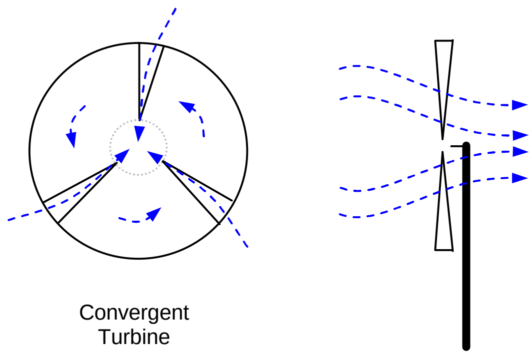


**Fig. 2** Expected lines of force for the *convergent* turbine.

As mentioned earlier, the double turbine system presented in this article uses this last principle.

## 3. Why double turbines

When using the usual *divergent* wind turbines, it perhaps makes little sense to install two turbines in a row for receiving a higher quantity of wind power along the same axial direction. With the dispersive behaviour they have, and since they may easily enter turbulent regimens, this would probably produce only a few positive results, unless the turbines would be separated by a long distance. It is perhaps due to this fact that double rotors of divergent turbines are not usually seen in wind systems. Exceptions are the multi-rotor horizontal systems recently proposed by Douglas Selsam[2], in the USA (Wikipedia, 2006).

But when we think on using *convergent* turbines, it becomes somehow reasonable to think of trying to collect also the power of the wind that passes freely through the transparent central spot. Associating two turbines with a certain separation between them (we suggest that this distance can be of the order of the rotor's radius), will in principle let us capture torque in two sections of the flow. These two contributions will certainly add, and the total power captured by the system will increase in accordance. From the observations made with the *double convergent* system we have built, we may note that we had the impression that the wind passing through the central spot tends to "open" again after traversing the turbine, and may therefore also be captured by a similar turbine strategically located some distance away. This idea is better

[2] http://www.selsam.com

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depicted in figure 3.

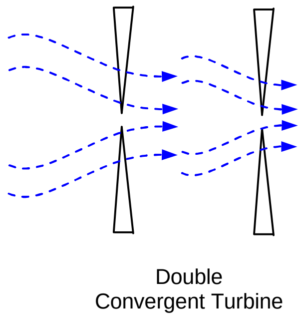


**Fig. 3** Probable lines of force in an association of two *convergent* turbines.

If this is true, one may even build a static system with good efficiency by simply installing two *convergent* turbines attacking the same axis of rotation, for example, as shown in figure 4. We expect that, in places where the wind maintains a preferential direction, this can be an interesting solution, since its instalation is simple and there is no need to worry about any special control. In extreme situations, the system can be repositioned in accordance with, in order either to get the maximum power or for protection during storm conditions. Such a control could be made electronically and in the overall structure, for example.

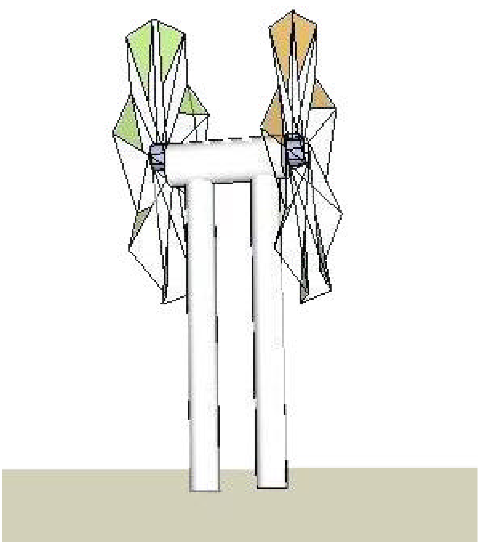

**Fig. 4** A static double *convergent* turbine system.

Apart from these comments, we also believe that *convergent* turbines will probably resist strong winds much better than *divergent* ones, since they tend to be more “transparent” to the wind flow. That would also mean substantially less control.

## 4. On following the wind direction

Most of the actual wind systems which track the wind are based on the tail vane principle. Some of these systems use this principle also to protect the wind system from excessive wind speeds, turning it appropiately above a certain speed limit.

The usage of *convergent* turbines also led us to test other solutions for tracking the wind, and these solutions showed to work perfectly if the machine is properly designed. The physical principle is the same as that of the tail, but now the tail is replaced by the second turbine (fig. 5).

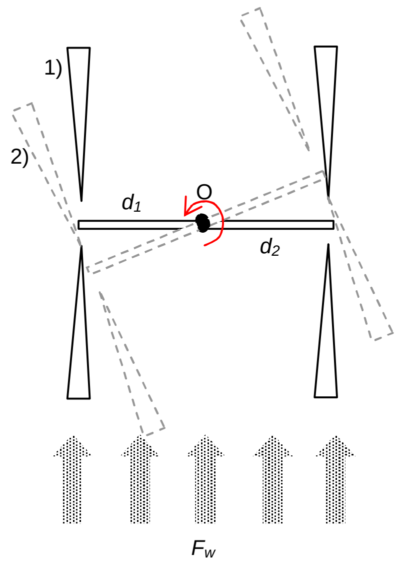


**Fig. 5** Tracking the wind direction with a double *convergent* turbine (top-view).

Supposing that the system starts in the position 1), with the two turbines mounted around a common axis of horizontal rotation ($O$), and parallel to the wind flow ($F_w$), the structure will rotate acordingly to the difference in torque introduced by the wind force in the two parts of the system. If, for example, $d_2 > d_1$ and the exposed area of both turbines ($A_j$) are equivalent, then the system will rotate as shown in the figure. Care must be taken, nevertheless, to avoid deceptions, since what must be compared is not only distances, but torques, which are computed by the product $F_w \times A_j \times d_j$, where $F_w$ is the force of the wind per unit of area. This means that there are two degrees of freedom in which the builder can act, considering $F_w$ common to both turbines: the distances $d_j$ and the areas $A_j$.

There are, however, some subtleties in this method which may result in a poor tracking performance, and induce a continuous horizontal rotation in the structure. In effect, the structure must be properly dumped in order to avoid this “excessive” rotation, and the distances ($d_j$) and areas ($A_j$) properly chosen. To avoid entering further mathematical details, we may say that using a larger blade area in the second turbine will surely help. If this is resolved, the system will perform perfectly.

Another important aspect to bear in mind is the *angular momentum* produced by the rotors at high speeds. As we know, by the law of conservation of angular momentum, the higher the rotational speed, the higher the momentum and the more difficult it is to rotate the structure horizontally. So, when one tries to force the turbines to change the plan of rotation, in order to adapt them to strong wind conditions, for example, stronger reactive forces are also induced in the support structure. If the turbine is quite light, this effect is reduced, but in systems for high power, with large areas of exposure to the wind, this effect must be studied before installing the machine. The *convergent* system shown in figure 6, for example, uses triangular blades mounted as “flags” in order to rapidly reduce the exposed area in high speed winds.

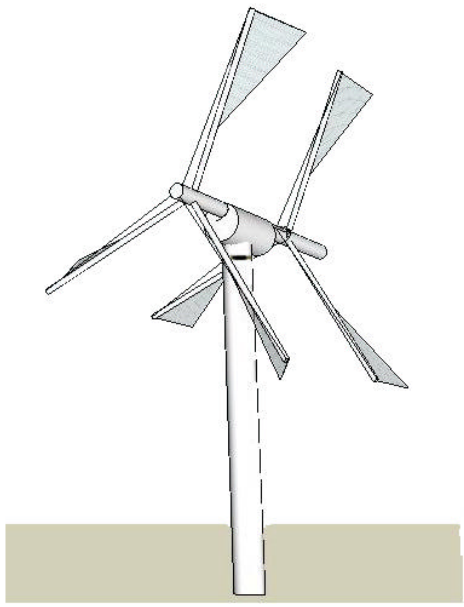

**Fig. 6** Another example of a double *convergent* turbine, with the ability for tracking the wind direction and reduce the exposed area during high speed winds.

## 5. A first prototype

The prototype presented in this section (fig. 7) uses two turbines built with the technique exposed in Feliz-Teixeira (2006). Please refere to this article for any details about the turbine construction. This *convergent* system can also be seen running, and tracking the wind, in two short videos offered at the Internet address http://www.fe.up.pt/~feliz.

**Fig. 7** Our double *convergent* turbine 1m in diameter, built of wooden sticks and blades made of TESA® adhesive tape. The system has the ability for tracking the wind.

This system uses two *convergent* turbines made of wooden sticks, and blades built of TESA® adhesive tape, a surprising resistant and light material. This tape can be used for making the blades of certain convergent designs, making them very attractive in terms of simplicity and costs. Even if one can hardly notice from the picture, each of these turbines has a tense wire around to confer rigidity to the structure. This method can also be seen in the typical Portuguese windmill, which inspired this turbine design.

The two turbines are then fixed onto a single horizontal shaft, separated by a distance of around 0,5 m. The shaft is then placed in a vertical support where it is able to rotate in the horizontal plan. With a diameter of 1,0 m, this rotor is expected to receive a direct power of around 450 *Watt* at wind speeds of 35 *Km/h*. Notice that the blades of the first turbine are thinner than the ones of the second, so that the system can better adapt to the wind direction. The efficiency of the system is still to be measured, and we would like to receive some feedback data from those readers who may be interested in helping to test this idea. We anticipate, anyhow, promising results, since this is a double system which is expected to capture the wind power in two plans and this way increase the total torque induced in the shaft.

This system has also been observed performing perfectly during a windstorm with winds in the order of 70 Km/h, and the tracking system previously disabled. In the end, the vertical support was broken but the turbine system remained completely unharmed. We could not record any videos of this situation, unfortunately, since we observed the storm during the night.

## 6. The Wind Forest

Somehow surprisingly, it is common today to find a strong inclination for taking into account aesthetic considerations when making the decision of which wind technology and system to use. In some way it is understandable, since machines like these are in certain conditions to be imposed for several decades on the natural environment; it seems a good idea to choose their design also in a way that it affects the tranquillity of nature as little as possible. The tranquillity of nature, however, is not properly our own tranquillity, since nature for instance feels the wind blowing and the shaking of its elements, like the trees, for example, as rich phenomena, while most of us choose to stay at home in moments like these. What seems good for us does not always have to be good for nature, we would say. In that sense, efficiency and reliability could be the universal measure instead, and perhaps the systems that we would install would simply be the best ones in terms of efficiency and reliability. That is, the ones which fit best with the natural laws. This issue is frequently touched apropos the type of tower that technicians and designers must choose for supporting the wind turbines, for example. Some people avoid the use of metal towers, which can be much more transparent to the wind than the usual single towers, simply because they do not look as nice as these ones. Our point is this: we believe that if a system is really good, the human mind will naturally adapt to it and recognize it as somehow making part of the laws of nature, even if it looks strange at first sight, perhaps. We must not forget that it is, somehow, of this strangeness that technology and science live. The best science and technology have always moved in the domain of the strangeness, and not in the opposite, the normal, the previously fitting and easy-to-absorb already "humanized" universe.

We have chosen this little introduction in order to present what we see as an interesting element of technology design, which we have named the *Wind-Forest*. The double turbines resemble trees (fig. 8), which will move as the other trees move when installed in the natural environment. If there is calm, they will move calmly; if there is storm, they will move fast, as it is normal for a tempest.

**Fig. 8** Double *convergent* systems located near each other, resembling trees.

Since these turbines can, in principle, be located much nearer to one another than those of *divergent* systems, which must be separated by some hundred meters, probably it would be easy to build a wind park for electrical power generation resembling a kind of forest, a technological forest, the *Wind-Forest*. In effect, if the expected transparency of these systems will let us install them much closer than usual, this is possible. There is in this idea the consideration not only of more power per square metre of occupied land, but also more power generated by each double turbine. This, in conjunction, could perhaps allow the use of systems with smaller diameter located not as high as the ones of today, in order to get the same amount of energy. This is, of course, a little divagation, which would need to be studied in detail. It represents, however, a certain wish of seeing technology resembling the design of the natural structures too. That would be good. Or even superb.

Thus, instead of being planted solely at the top of the mountains obstructing our view of a clean and peaceful sky, these *Wind-Forests* could perhaps be planted along the slope of the hills, or in any plain landscape, in that way becoming part of nature. Blades may even be painted green, when needed, for example. We end this section with an artistic view of this idea, and with no further comments:

**Fig. 9** The vision of a *Wind-Forest*.

## 7. Conclusions

We presented here a *double convergent* turbine for wind power capture. The results obtained by inspecting the system operating are stimulating and led us to believe that this can perhaps be a good solution to be used in practice, at least in systems of small and medium scale. The turbine structure proved to be reliable in terms of wind response and of rigidity, being perfectly rigid at wind speed in the order of 70 Km/k. With respect to its construction, this system is simple, flexible and inexpensive. Several systems of the kind could probably be installed as a dense area for collecting the wind power and transforming it into electrical energy, leading to something resembling a forest of wind systems, which we called *Wind-Forest*. Most of the ideas presented in this article are still to be confirmed in practice by means of some tests and experiments.

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# Low-cost Convergent Turbine for Wind Power Usage

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KEYWORDS: Renewable energy, wind power, “convergent” and “divergent” turbines, windmills, electrical generation, inexpensive solutions.

## ABSTRACT

Here we describe the concepts related to what we consider “divergent” and “convergent” turbines and use these concepts to support the introduction of a new turbine for wind power capture. This is a low-cost turbine which can easily be build with ordinary materials, to a certain extent inspired by the old Portuguese windmill used to grind grain into flour. Mainly due to the simple construction, the low-cost of its materials and the surprising performance observed in practice, this system can be seen as an interesting alternative to the expensive wind turbines presently offered in the market. This is, however, a proposal that has not yet been verified by accurate scientific measures in order to be compared with the performances achieved by the usual turbine design. We invite the reader to contribute to such a task, should s/he find this an interesting subject. We also expect to simulate the concepts presented as soon as the time and financial support allow it.

## 1. Introduction

As a first remark, we would like to state that any novel ideas presented in this article are to be considered anti-patent, that is, they are offered to the public domain by its author and anyone may implement them freely without the need for any special permission, other than a symbolic contribution in order to cover the author rights. Please contact the author, in this case.

The energy contained in the blowing of the wind has been used by humankind for a long time, as we know, and sailors are perhaps those who have better experienced the power of such a source of energy. In effect, most of the geography of our Earth was “discovered” by people moving by means of wind power. Additionally, this energy was also used for pumping water and for grinding grain, for example, in systems known as windmills. Some of these practices seem to have remained stable for a long period of time, perhaps for even more than a millennium, with some of them still being used today, like the sailing vessel and some windmills in places that are still under development. At the end of the 19$^{th}$ century, however, a slow revolution was starting with Charles F. Brush in America and Poul la Cour in Denmark who were dedicated to developing automatically operating wind turbines for the generation of electricity (D.W.I.A., 2003). These can be considered the pioneers in using wind energy for electrical power generation. It is interesting to notice, however, in particular when we focus our attention on windmill systems, that mainly two approaches for capturing the energy from the wind are employed: in the first, there is the tendency for capturing this energy with several blades which the force of the wind drives around an “opaque” centre of rotation. This is the case of the well- known Dutch windmill, for instance, extensively used for pumping water. In the second case, there is the tendency to use sails located at a distance apart from a “transparent” centre of rotation which capture the peripheral wind force and use its superior torque for turning around a circular structure. This is the case of the ancestral Greek windmill, of which the Portuguese windmill is a particular case. Figures 1 and 2 give a better idea of these two types of methods for collecting the energy of the wind. There are also other methods that use vertical shaft turbines, like the old Chinese and Persian windmills configurations, but these systems are usually seen as being less efficient than those using the horizontal shaft scheme. An interesting overview of several wind turbine schemes can be found on the Heiner H. Dörner's webpage[1], among other Internet sites.

**Fig. 1** The Dutch windmill, showing an "opaque" centre of rotation around which four blades move with the force of the wind.

**Fig. 2** The ancestral Greek windmill, with a "transparent" centre of rotation where the wind can flow freely, and several sails mounted apart to capture the peripheral superior torque of the wind.

Based on these two configurations, we will soon talk about our idea of "divergent" and "convergent" turbines. For an excellent lecture concerning wind energy and electrical wind generation, the reader may find it very useful to visit to the *Danish Wind Industry Association* website[2]. Anyone interested in knowing more about modern wind energy should visit this site on the Internet.

It is also interesting to notice that the usual calculations of wind turbines are based on the aerodynamics of the wing, considering the *lift* and the *drag* effects, but here we use a simpler form for interpreting the wind flow phenomenon, trying a more holistic perspective where physics will be mixed with a certain intuition. This may therefore be considered not completely scientific in the sense of a Kantian reasoning, since it perhaps goes more in the direction of a Bergsonian[3] perception of the phenomena. In such a perspective, we try to use the knowledge of physics and engineering as tools for the intuition, that is, so that the analyst can make himself "feel" what the wind particles "feel" while traversing the turbine system. As Bergson would recognize, this is as if the analyst would have the ability of transforming himself into the wind or into the turbine. Such a perspective is different from the *empirical* approach, since *empirical* knowledge does not count with such a theoretical understanding of the laws of physics. In a way, this can at least be seen as a good exercise on three-dimensional (3D) abstraction, since there is the need for predicting the behaviour of the fluid and of the turbine system in a sort of an imaginary 3D game.

## 2. Divergence and convergence

In general we call a *convergent* system a system which transforms the dimensions of a certain type of flow into a more compact form, therefore reducing the space occupied by the flow and increasing its velocity or its density. On the other hand, a *divergent* system tends to expand the lateral dimensions of the flow, therefore inducing a decrease in the velocity or in the density. A typical example is the case of deflectors of electromagnetic radiation, which for light are known as optical lenses. Another simple convergent system is the funnel, for example, and a divergent system the opened doors of a stadium at the end of a match. If one thinks on some other convergent and divergent systems one may somehow intuitively associate convergence with an organized although tense movement, and divergence with a certain dispersion

[1] http://www.ifb.uni-stuttgart.de/~doerner/edesignphil.html
[2] http://www.windpower.org/en/tour/wres/index.htm

[3] Henry Bergson, a French philosopher from the beginning of the 20th century, who considered time as a history, instead of as an event or as a distance.

coming from the fact that each particle is getting freer of interactions than before. It is therefore expectable that turbulence is frequently observed in divergent systems, resulting from the natural dispersion introduced by its geometry, in particular at the system's boundary (see fig. 3). Sometimes interference phenomena are also observed in this region, if the dimensions of the system are comparable to the wavelength of the particles in motion. All this, of course, may represent a significant loss of energy, since the elements of the flow have meanwhile lost the "synchronism" they previously had within the motion.

On the other hand, in convergent systems the energy of movement tends to follow a path of concentration (fig. 3), which in the case of fluids and systems of particles results in an acceleration of the flow most of the time. There may also appear some interference between different parts of the flow, but there is no dispersion and a higher concentration of the energy is due, which therefore may easily be captured, in principle.

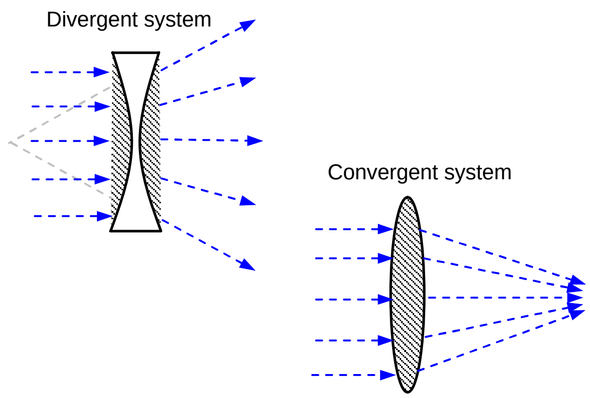


**Fig. 3** The concepts of *convergence* and *divergence* as they are understood in optical systems.

## 3. Divergent and convergent turbines

Following the thoughts of the previous section, we may now introduce the idea of divergent and convergent turbines. With this purpose, let us imagine two circular areas of the same dimensions, each one rotating by means of three blades, for example, as shown in figure 4. In the first case (turbine A) the blades are mounted on an opaque centre of rotation and in a way that the torque is approximately constant along the blade length. In the second case (turbine B) the blades are mounted from the periphery towards the centre of rotation, which is transparent in the sense that it represents no obstacle to the flow, and the geometry of these blades is chosen in a way that the torque is made to increase towards the periphery. The inclination of the blades in respect to the plan of the turbine is important, but here we may consider it to be 45º in both cases, since we will mostly consider the drag effect of the wind at the blade surfaces. We may also suppose that both turbines run to the left, for instance.

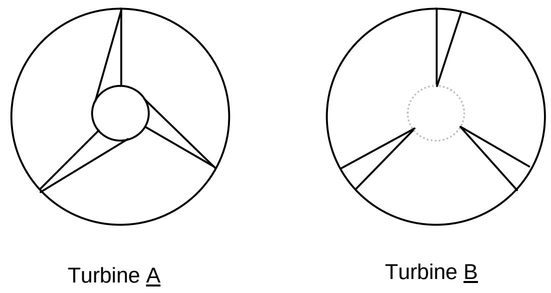


**Fig. 4** Basic shapes to assist in explaining the idea of *divergent* and *convergent* turbine.

Now, if I imagine myself forming part of a huge group of particles interconnected by some elastic forces, as a first approach of the fluid, which are moving in a synchronized way in a regime of constant speed and suddenly meet one of these turbines in their way, let us see if we can imagine what will happen and how the flow will behave. Let us begin with the turbine A.

As we are now highly deformable, the first thing my group of particles will do at the moment of the first impact with the turbine is to assume the aspect of the turbine itself, as in a process of getting formed by a mould. After that, the form of my group of particles will be distorted principally due to concurrent forces of pressure, drag, elasticity and centrifugation. The first of these forces results from the sudden obstruction to those particles moving near the centre of the turbine, since this is "opaque", compared with the almost free movement of those which are traveling in the periphery. The drag force is mainly coming from the drag impulse imposed by the blade in its movement. The elastic force results from the reaction of the particles to these movements as an elastic coerent medium. The centrifugation is naturally produced by the inertia of the fluid while "refusing" to rotate.

Thus, if we imagine being the particles moving in this complex process, some of us are forced to compress and then to slip at the blades, due to the velocity with which the turbine impacts on us. At that moment, we realise that the turbine starts to rotate to the left and we feel compelled to do the same during the time we need to traverse the turbine depth, being under the drag force effect. Different directions of drag in the different blades and the natural elastic forces ensuring the medium continuity introduce a rotation in us all, from which we therefore feel a centrifugal force moving us in the direction of the peripheral part of the turbine. So, we are compelled to rotate with the turbine at the same time we move apart from the centre, pushed away by the higher central pressure where many particles first tend to gather on the first impact. Once we reach the peripheral lower pressure, we will feel again somehow free of the stress introduced by the turbine, and in certain cases we will disperse in the air. This behaviour is schematicaly represented in figure 5.

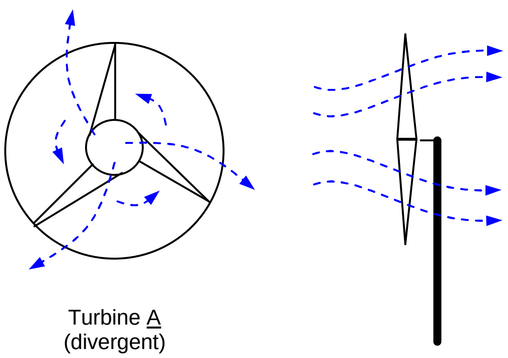


**Fig. 5** Expected lines of force induced in the flow in a *divergent* turbine running to the left. Frontal and lateral views.

Let us now imagine the same situation, but with the turbine B. Once again, in the moment of the first impact with the turbine the group of particles tends to assume the form of the turbine itself, which is now less complex than in the previous case, since there is no central obstruction. Then, it will be also distorted by the influence of forces of pressure, drag, elasticity and centrifugation. In this case, however, the pressure forces result from the obstruction made by the blades to those particles moving near the periphery of the turbine, since this turbine tends to be "opaque" in this zone, compared with the almost free movement of those which travel along the central aperture. The drag force is again coming from the drag imposed by the blades, the elastic force from the coercion of the fluid, and the centrifugation from the rotational inertia. Thus, when the impact of the blade hit us, particles moving near the periphery, many of us are forced to compress and then to slip along the blades, making the turbine turn, and then we slip either in the direction of the periphery, if the drag impulse plus the centrifuge force is superior to the vacuum force coming from the centre, or in the direction of the centre if this vacuum force is stronger (fig. 6). We realise, however, that the turbine is rotating to the left probably not only due to the first impact on the blades, but also due to our forced slip through these while being sucked to the central vacuum, which at high speeds may start to resemble a little tornado.

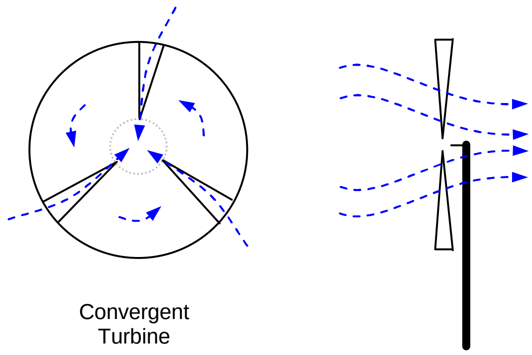


**Fig. 6** Expected lines of force for the *convergent* turbine.

After this simple trip with the particles, we start to believe that convergent turbines can even be more efficient than divergent ones, as well as the possibility that we can expect less turbulence of them, higher resistance to fatigue, easy to build, much easier to start running, probably less noisy too, and being much less expensive. In order to reduce tip effects at high speeds, as well as keeping the noise generated by the turbine low, the blades in the periphery of the convergent system may be kept parallel to the turbine movement, reducing friction with the air.

## 4. A curiosity about the *Betz limit*

As a curious detail, we would like to recall that the so called *Betz limit* was computed on considering the behaviour of a *divergent* turbine system, and not the dynamics of a *convergent* one, and for a constant fluid pressure along the plan of the turbine. For good mathematical detail concerning fluid flow in turbines, please see (Corten, 2001; Gorban et al., 2001), for example. So, when from the Betz approach we conclude that

59% will be the maximum achievable efficiency for any sort of wind turbine, we may, perhaps, be too severe. Anyhow, it is not our intent to confront such a mathematical analysis in the present article, since at the moment we are more interested in reasoning from a particle-like perspective, which we expect will be useful in our future commitment to a microscopic simulation analysis.

## 5. The perfect convergent turbine?

From the last discussion, we may expect, once again by means of intuition, that a good design for a convergent turbine may be of a conical shape, since that way more fluid will be forced into the direction of the central transparent spot, where the pressure is lower due to the vacuum induced by the free wind movement in that zone, and by rotation. Figure 7 aims to represent such a layout.

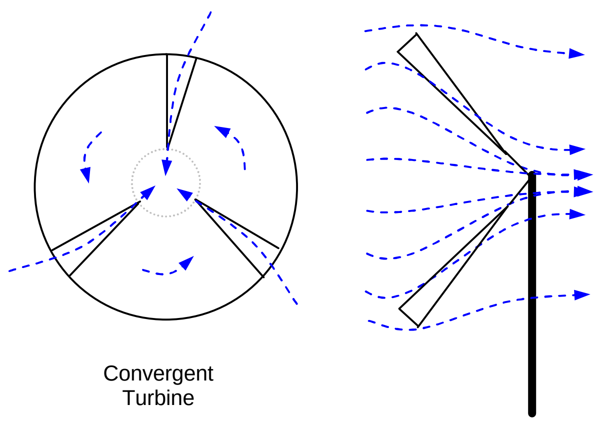


**Fig. 7** A *convergent* turbine with the shape of a funnel.

In a turbine of this kind, wind would in effect tend to slip down the blades to the centre, where it would also rotate driven by the movement of the blades. Such a design would also help to minimize the amount of fluid that coud simply pass around the border of the system. We would even expect, perhaps, the central pressure to become lower than the atmosferic pressure at high rotational speeds. All this would, in principle, optimise the amount of wind power captured by the system.

Evident problems arising from such a design are, in our point of view, the complexity of the process to build the turbine and the dificulty to install it in the wind tower, since its blades are inclinated and the structure is unbalanced in terms of weight distribution. Such an assimetrical structure would also require very special care for it not to become highly unstable with wind turbulence, for example.

## 6. An easy-to-build convergent system

We will finally present in this section a very simple *convergent* turbine, which anyone can build even at home using the cheapest materials and the simplest tools. The rotor dimensions may be chosen in accordance with the particular energy requirements, and no special concerns are due to turbines of different dimensions, other than the usual cautions about the resistance of the materials employed, since the wind power increases with the square of the *turbine radius* and with the cubic law of the *wind speed*:

$$P(Watt) \propto r^2 v^3 \qquad (1)$$

To help the reader get an idea of the amount of wind power entering a wind turbine, here we show some simple expressions:

$\rho$ = 1,2 Kg/m$^3$ – density of the air
E = ½ m v$^2$ – wind kinetic energy
S = $\pi$ . r$^2$ – Area of the rotor (turbine)
P = 1,9 r$^2$ v$^3$ – Wind power received (Watt)

For a turbine (rotor) radius of 10 meters, these equations lead to the following data (notice that the power of a wind system is usually given for a wind speed of around 40 Km/h):

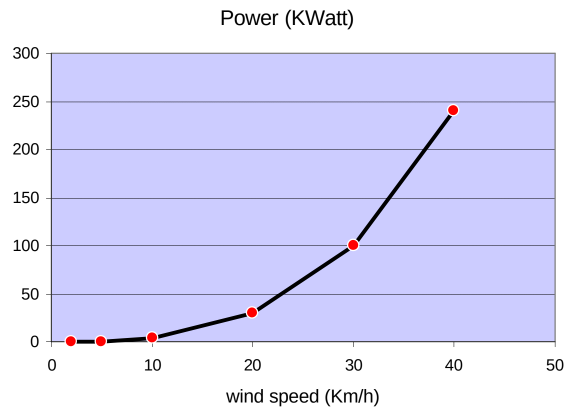


**Fig. 8** Power received by a turbine of 10 m radius.

This means that more care must be taken when testing or installing turbines of increasing dimensions, and always avoid handling them on windy days.

We may now proceed with our convergent turbine construction. For that, one can simply get a rod of wood or a metal tube in which four holes have to be made, as depicted in figure 9. Notice that these holes make two sets of parallel lines differing by a rotation of 90º.

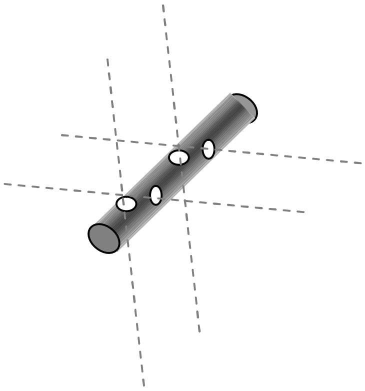

**Fig. 9** The base support for the *convergent* turbine.

Now, simply insert along these holes, four other sticks, of wood or aluminium tube, thinner and longer, which will define the turbine's diameter. The structure must look like the one depicted in the next figure (fig. 10).

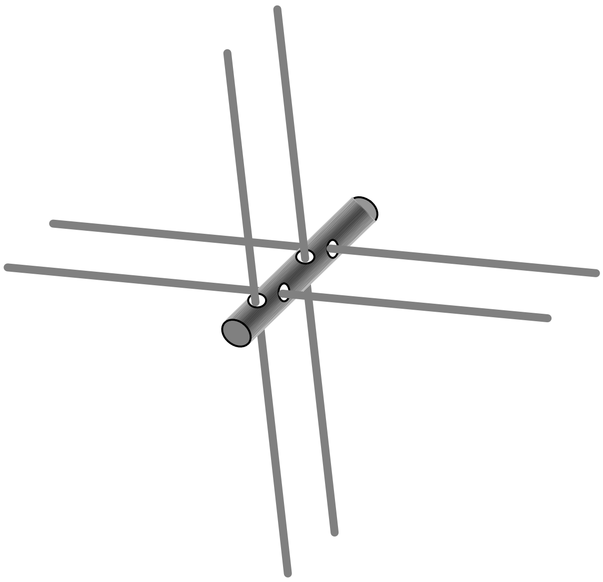

**Fig. 10** Inserting the supports for the blades.

This is the structure of the most basic convergent turbine, two steps from being ready to use. We would like to remind that it is extremely important that these rods will be well positioned around the centre, so that the rotor will be maintained in a good equilibrium. This, of course, will have influence on the minimal wind speed at which the system begins to turn. These long rods giving the base for the future blades may be of any material that is light and resistant enough to support the wind power captured by each blade. Many common materials will work for low speed winds, but the challenges are much higher at high wind speed regimes, as previously observed.

The next step is to use a wire to give the structure good rigidity, which can be done by simply rolling it around the tips of each parallel rod in order to connect them to each other, and then to its perpendicular neighbours, pulling it slightly to give the system a certain tension. The rigidity of the structure will come from this tension. The system will then look like what is shown in the next figure (fig. 11).

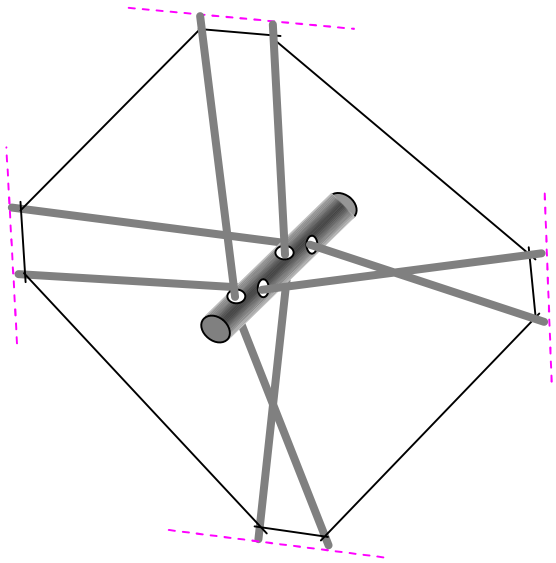

**Fig. 11** Preparing the blades' support and giving rigidity to the turbine's structure.

Notice that the tips of the rotor are now made almost parallel to the rotation plan, and this will reduce the friction with the air in the peripheral region. Notice also that if one uses an "elastic" wire in this type of construction, it is possible to build a system in which the blade area is automatically reduced as the wind speed increases, while at the same time the rigidity of the structure tends to get higher. This could turn out to be useful for designing turbines with a strong resistance to wind storms and with a controlled rotational speed. The maximum natural area of each blade may of course be computed as the *rotor radius* times the *distance between parallel holes*, but the maximum useful area can roughly be estimated as being half of this, taking into account that the wind faces almost no area at the central region, due to the structure design. One may also take the option of letting the blade start only some distance apart from the centre, as is commonly observed in the so-called Wind Rose American style windmills, since the torque in such a region is small and the wind will easily traverse the turbine. A complete view of this first convergent turbine is presented in the next figure (fig. 12).

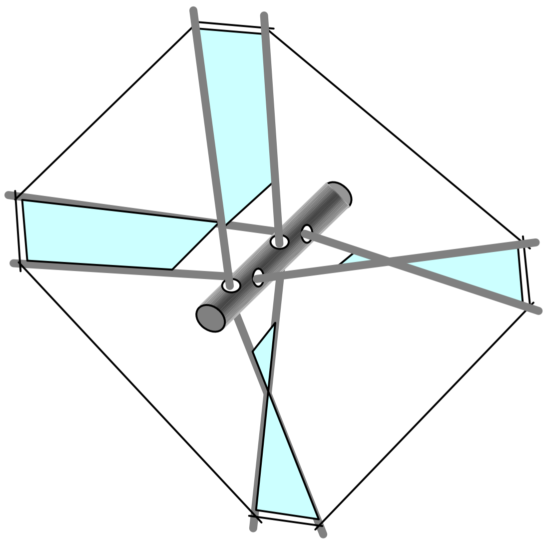

**Fig. 12** A simple convergent turbine with four blades.

Notice that since the system was given enough rigidity, one could then fill the space reserved for the blades with any light material. This can be done with four pieces of cloth taken from an old camping tent, for example, which then are mounted tightened between the arms of the blades. An easy, nice and faster approach is to make the blades with several pieces of transparent TESA® adhesive tape, glued along both sides of the blade. This tape is resistant enough for testing the turbine performance. Thus, being already in the possession of the materials needed, mounting one of these turbines hardly would take more than 15 minutes!

Another interesting feature observed in these turbines is the rigidity of its tips, since these are continuously under the tension maintained by the wire; unlike what usually happens in most divergent turbines, where blade tips easily vibrate and obviously create great instability in the entire wind machine structure. Notice also that a structure of this kind can be made very light, if the technology of materials is employed in its construction, for instance, using reinforced fibreglass or carbon fibre.

## 7. The eight blades version

We may now expand the idea for any number of blades, as long it is a multiple of four. In this section, we show an example of how to append extra four blades to our turbine, by adding four more holes in the base rod with an inclination of 45º in respect to the previous ones. The next figure (fig. 13) helps to visualize the frame resulting from this.

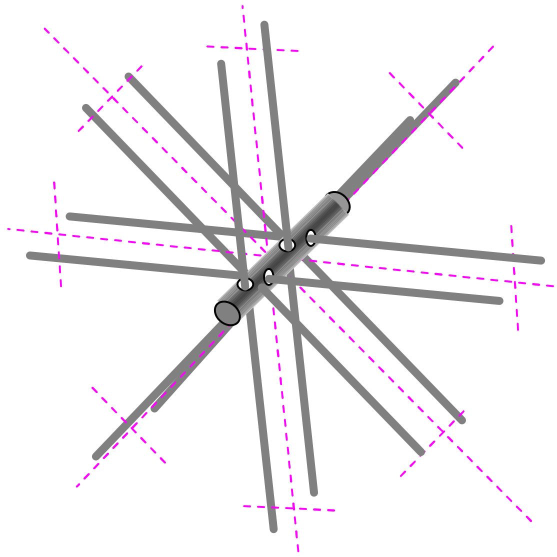

**Fig. 13** The eight blades basic structure.

Finally, figure 14 shows the complete turbine with eight blades ready to operate. Such a rotor will obviously run easily than the previous one, since it is able to capture a superior torque from the wind.

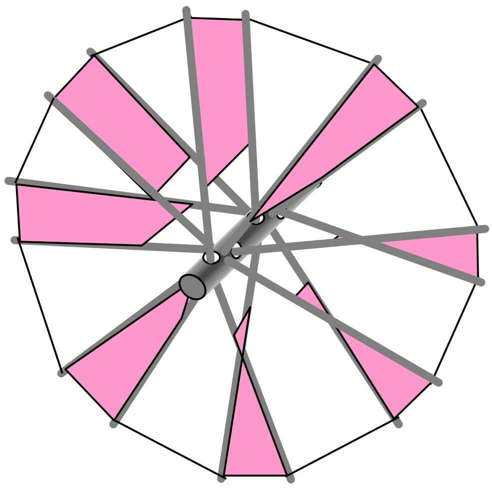

**Fig. 14** The complete eight blades wind turbine.

## 8. Comparing with the Portuguese windmill

The beautiful windmill depicted in figure 15 is the typical Portuguese windmill. It may be found mainly in the south of the country. For a long time these systems were systematically used to grind grain for the population. Such a system of sails is also simple to manage, helping the miller in his control of the machine, since he can adapt the sails configuration to the actual wind speed by changing the area exposed to the wind.

**Fig. 15** The typical Portuguese windmill.

As we can see by the arrangement of sails, this mill uses a convergent turbine concept to capture the power of the wind. The sails are, nevertheless, mounted on the structure of wooden rods in a way slightly different from what we propose. In effect, there is a large area of exposure in each sail, and that is expected to reduce the efficiency of the system. From the figure, one can see that the wind seems to stagnate when it is captured by those sails, instead of rapidly traversing the turbine. This, of course, is expected to create useless pressure on the mill house instead of contributing to the efficiency of the machine.

On the other hand, the configuration we propose does not allow this to happen, since instead of contributing to the stagnation of the wind, it forces it to slip along the blades. Consequently, it also increases the transparency of the overall turbine, which is known as a good practise for wind power generation systems. In rotors of high diameter and substantial number of blades, the transparency can also be increased by reducing the distance between the parallel holes in the base rod which supports the structure, at the same time reducing the drag but also the friction with the air at high speeds.

## 9. The observed performance

As we pointed out at the beginning of the article, there has not yet been an experimental measure of the performance of this convergent turbine, in order to compare it with the divergent ones offered in the market. We have, however, built a rotor based on these ideas one meter in diameter (fig. 16) with which we have observed a very good response in a wide range of wind conditions. In effect, this turbine showed to work steadily with wind speeds in the order of 3 or 4 kilometres per hour, and maintained a good shape and rigidity while running much faster during a little windstorm. The impression is that this is very efficient design, and, what is also impressive, that it is extremely silent, since no sound was ever coming out from it.

**Fig. 16** A model of a 1 m diameter convergent turbine built of wood sticks and blades made of TESA® adhesive tape.

## 10. Other convergent designs

The idea of a convergent turbine can lead us to imagine other types of structures to capture the power of the wind. The one presented here was simple, resistant, and much less expensive than any of the wind turbines offered in the market. In fact, it was built with materials bought at an AKI storehouse. Anyhow, there is another design deserving attention, mainly due to the ability to automatically adapt the area of exposition of its blades do the wind speed. We are in particular talking about the system shown in figure 17:

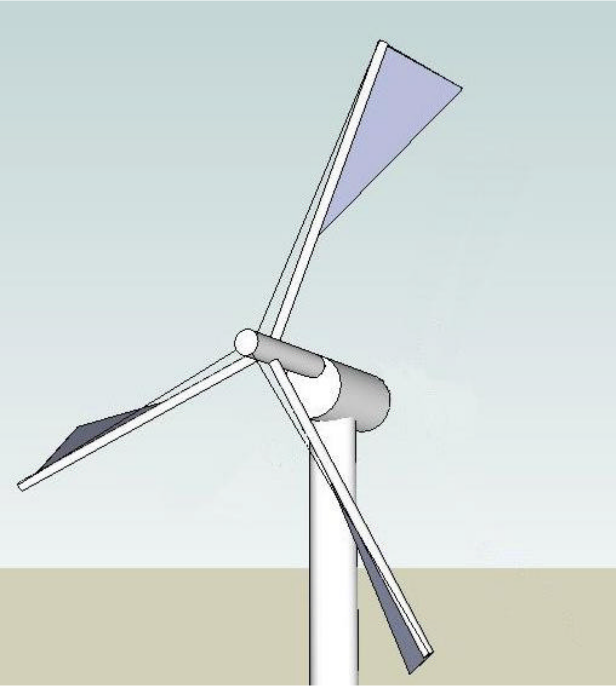

**Fig. 17** Another convergent turbine with blades that automatically adapt to the wind speed.

This system uses blades in the form of triangles mounted on the respective rods in a way that they can follow the wind, as flags do. When the intensity of the wind is very high, they will assume the direction parallel to the wind flow and therefore minimize the overall wind impact in the turbine system. This may be extremely useful to achieve a good behaviour in the case of storms. On the other hand, when the wind speed is low, the blades will naturally assume an inclination of 45º, for example, by means of some kind of restoring force produced by a spring or any other simple mechanism.

## 11. **Conclusions**

As a result of the ideas exposed in this article, we may conclude that anyone can afford a *convergent* turbine for capturing the power of wind, since the materials needed to construct it are in effect inexpensive and their assemblage relatively simple. Compared with the prices asked on Internet sites, for example, which still make most of the wind systems unavailable to the population, these new turbines could represent a good solution to anyone interested in making use of the advantages of renewable energies. At the same time, although there has not yet been an experimental confirmation concerning the real efficiency of the *convergent* systems presented in this article, we expect them to be perhaps more efficient than the normal ones, since the process of capturing the wind power is slightly different from that used in the familiar *divergent* turbines. This fact also makes us wonder if the *Betz limit* of 59% maximum efficiency could be somehow debatable, in the case of a *convergent* system.

Finally, we welcome any contributions to the testing, developing, spreading or implementation of these ideas, which we would applaud with pleasure since it would mean a turn to handling the energetic resources of our planet more reasonably.

**Author Biography:**

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# Roda-de-Vento, a Proposal for an *Ex-libris*

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KEYWORDS: Wind energy promotion, arts and technology, architectural installation, wheels and wind sports.

**ABSTRACT**

The idea described herein is a proposal for an artistic-technological installation on the coastline of Porto, Portugal. The aim is to install in a seaside esplanade a giant bicycle wheel (*Roda-de-Vento*) which will turn with the wind. This element will be both an architectural construction praising those who often use the esplanade for riding bicycles, roller-skating, wind-cars, etc., as well as a wind electrical generator, aimed to directly promote to citizens the potential hidden in renewable energies[1].

## 1. Introduction

During these last years, the coast of Porto and of its neighbouring towns has observed significant transformations due to general works. These have started in the wake of the event "*Porto2001-European Capital of Culture*", and were prolonged for some years till nowadays with an intensive change of the town's view. Despite the long time passed in works, and the negative effects that such a situation had brought to the population, some of the spaces have definitely changed for the better and have even stimulated people to change their own habits. The most important was a surge in the outside door practice of walking and sports. The two works deserving special mention, in our point of view, since they had effectively contributed positively to a better life in the town, were the creation of the "*Parque da Cidade*" (City Park), an extensive and natural place where people started to engage with nature, as well as walking, running, etc., finally fulfilling the urgent need for a natural place to compensate for the saturated ambience of the inner city, and the "*Passeio Alegre*" (seaside esplanade), where a way of several kilometres for walking, cycling, roller-skating, etc., was also built along the seaside.

The interventions in these places were diverse and of various types, including architectural and artistic, but time has shown that the most important aspects achieved with those works were the dynamics created in the population by simply opening and making available places of such importance. In effect, each of them represents nowadays a place of choice for many people, where life runs in its most natural and healthy form.

The subject of this article is related to the preservation of such a spirit and to a trial of including in it the interesting approach of renewable energies (in this case, from the wind). The running wheels of the bicycles and roller-skates that can usually be observed moving along the seaside esplanade, as well as the wind cars and wind-boards, kiteboards, etc. which may also be found there, represent most of the inspiration for the present proposal. The remaining contribution was due to some giant bicycle wheels installed in some places around the world for diversion purposes, as the one presently installed in London, next to the *Thames*, or the one installed in a place for skating in Japan, represented respectively in figures 1 and 2.

**Fig. 1** Giant bicycle wheel installed near the Thames, London, for diversion

**Fig. 2** A similar type of wheel installed in some place for skating in Japan

## 2. The present situation

Bordering one of the sides of "*Parque da Cidade*" (City Park), and extending along several kilometres north-south next to the Atlantic Ocean, the seaside esplanade is at present, as mentioned before, a way for people to enjoy the pleasures of breathing the sea air, walking, the beach, and the practice of sports. Nevertheless, the presence of tourists in such areas is rare, perhaps because it is a futuristic place and in effect with no special motifs for the photographic cameras. Besides the little castle which stands in a corner ("*Castelo do Queijo*"), nothing there seems yet to contain history or any interesting conceptual idea deserving the attention of a tourist. So, the space is simply noticed as being good for racing bicycles and to enjoy the pleasures of the seaside and, moving a bit upwards, for the nature of "*Parque da Cidade*". The next figures aim to give a better view of this site, more precisely of the place where we propose the *Roda-de-Vento* (wind wheel) to be installed.

**Fig. 3** Bicycling and roller-skating in the seaside esplanade, a view to the north, to the town of Matosinhos

**Fig. 4** View to the south, in the direction of Porto, with the little castle (*Castelo do Queijo*) visible, at the right

Although the practices of sports observed in this place already associate a certain movement with it, our proposal is that the installation of a wind wheel will operate as an architectural element of synchronization of such a movement, better integrating people's activity in the windy and wavy scenery, by means of a human construction. This may be the intention behind the artistic nature of the proposal.

In addition to this, however, and considering that the places around are already too crowded of divertive offers, our proposal has the strong objective of also inducing the fascination of renewable energies in people, as we said. For that reason, the wheel will also be used to transform the wind energy in electrical energy, we believe in sufficient quantity for satisfying the energy demand of several houses in that space (perhaps the bars operating in the beach). The next figure is another view of the site.

**Fig. 5** Another view to the south, in the direction of Porto

## 3. The Roda-de-Vento

We defend that the *Roda-deVento* must be developed in the dimensions of a giant wheel, at least 10 metres in radius, so that the construction emerges from the ambience and naturally transforms in a sort of signal, an *ex-libris*, being seen from far, and, that way, imposes itself to the ambience as the main synchronizer of the movements between the sea waves and the people's activities. During those hours that the activities are reduced or the site is empty, this wheel will be seen as a solitary and beautiful producer of electrical energy, exhibiting perhaps the maximum of its fascination. We have in mind to paint it in certain places with fluorescent ink, which will be best visible during the night.

The wheel presented in this article is not, of course, in its final design and dimensions, but solely represents a first approach to the idea. Nevertheless, the usage of a giant bicycle wheel, perhaps made of aluminium, as the basis for the wind turbine, is definitely the proposal, since it fits perfectly the two primer objectives of the project.

At the same time, we expect to enrich this system with a level of automation which will be principally used for security reasons in the case of very strong winds, which will make the wheel turn around by itself and face the wind direction with the minimum area, therefore reducing the impact and the probability of breaking the structure. This feature may, of course, be also appreciated as another interesting concept for those who visit the location. The basis for this system can, therefore, be something like that represented in the next figure (Fig. 6).

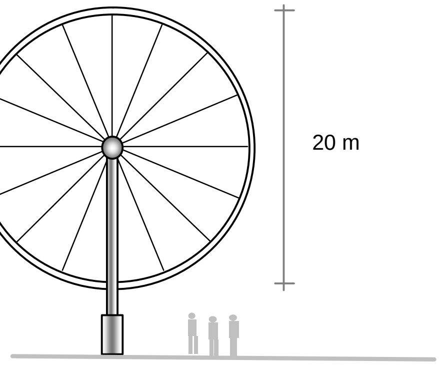


**Fig. 6** The basis for the *Roda-de-Vento*

The transformation of this bicycle wheel into an efficient wind turbine will be easy; also simple will be the incorporation of the electrical generators (in number of two) into this structure.

## 4. Energy retrieved from the wind

Considering such an apparatus and such wheel dimensions, calculations show that the wind energy captured by this system may well be enough to power the bars presently installed at the same beach. Such calculations were made taking in account the following mathematical relations:

$\rho = 1{,}2$ Kg/m$^3$ – density of the air
$E = ½\ m\ V^2$ – wind kinetic energy
$S = \pi\ .\ r^2$ – Area of the wheel
$P = 1{,}9\ r^2\ V^3$ – Wind power received (Watt)

For a radius of the wheel of 10 meters, these equations lead to the following data:

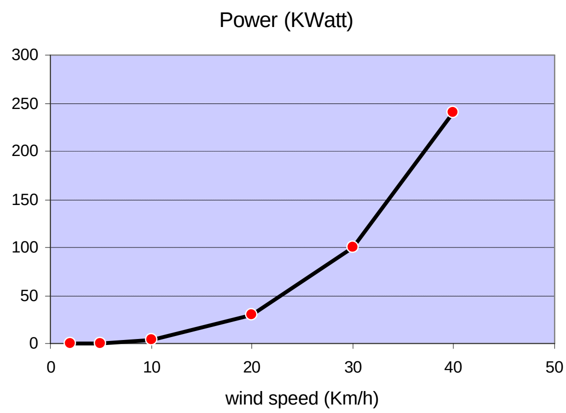


**Fig. 7** Wind power received by the wheel in the case of low and medium wind speeds

Considering that: (1) the wheel would have a power coefficient of 30%; (2) each bar in the beach would continuously demand 5KWatt for operation; (3) the wind in that place will normally have speeds between 20 and 30 Km/h (power received by the wheel would be around 30 to 100 KWatt); then the number of bars that could be served would be between 2 and 6. Of course, if the wind speed goes to 40 Km/h this number automatically jumps to more than 14. So, it seems perfectly possible to generate the necessary energy to supply the bars presently installed in the beach, since during the night they close while the generator continues to produce energy.

Notice that as the wind speed increases the power is increased by a cubic law (see figure 8), and, for instance, winds of 80 Km/h, which sometimes occur in the place, would represent a power of 2000 KWatt, enough to feed 120 bars!

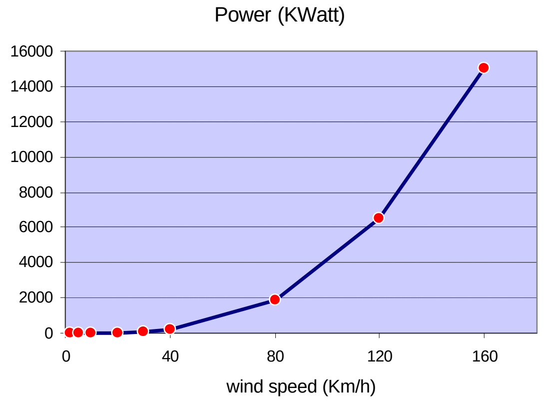


**Fig. 8** Wind power received by the wheel for the case of high and very high wind speeds (danger of break)

Wind speeds superior to this will probably make the structure instable, so the wheel must rotate in order to minimize the area exposed to the wind. This will dramatically decrease the wind pressure on the structure and adjust the power generated to a reasonable lower level, protecting also the electrical generators.

The simplicity of this system is leading us to believe that the project may entirely be developed with national technology.

## 5. A simulated view on the future

The next figures intend to give a brief idea of how *Roda-de-Vento* will look when installed in the place we propose. These views, representing the future, are taken precisely at the same site as those of figures 3, 4 and 5, which represent the present. So, the two situations can be compared. Through figure 9, for example, one can already get the idea of a synchronizing wheel, an environment synchronizer, while figure 10 shows the apparent simplicity of the construction and the way it lands in the scenery. It is interesting to bear in mind that the sea next to the wheel is usually used by people practicing surfing. Figure 11, shows the wheel in a turned position, as when avoiding strong winds.

**Fig. 9** The wheel as an environment synchronizer

**Fig. 10** The basic *Roda-de-Vento*

**Fig. 11** Wheel rotated, to protect from strong winds

It is important to mention that the simplicity presented here will not correspond to the final design of the wheel, since it is still necessary to include certain blades to collect the wind and impulse the system, even if those blades are in principal to be almost transparent, in the present conception of the work. We have in mind, in effect, to maintain the fascination of the wheel by the simplicity of the wheel in itself, which also will be made as silent as possible, at least compared with the sea sound, to create even more the sensation of being suspended in people's imagination. This is intended not only to be an artistic effect, but also a work where an interesting concept will be exposed and alive. Therefore we expect to make of this building an *ex-libris* for people in general and, who knows, even for Japanese tourists who for sure will enjoy photographing it.

## 6. Conclusions

As was stated in this article, the proposal of a giant bicycle wheel as an artistic-technological installation in the seaside esplanade of Porto is expected to help improving both the charm of the place and the promotion for the usage of renewable energies. In effect, this wheel, which we named *Roda-de-Vento*, will be seen not only as an architectural dynamic construction honouring those who practice sports at the place, but also as an electrical generator directly retrieving energy from the wind. Its capacity for generating energy is, of course, dependent on the final dimensions of the wheel, but based on calculations considering a wheel of 10 metres of radius, it is expected that enough energy will be generated to fulfil the needs of the bars operating in the zone. The proposal will, for both reason, add value to citizens' life and probably even to tourism. The construction may therefore be seen as a kind of *ex-libris*, and a curious attraction.

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[1] **IMPORTANT NOTICE**: The idea presented in this article is to be considered *anti-patent*, that is, it is offered to the public by its author and anyone may implement it freely without the need for any special permission, other than a symbolic contribution in order to cover the author rights. Please contact the author at feliz@fe.up.pt, in such a case.

# HiperJanela, an Upper Dimension for the Society of Information

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KEYWORDS: Information Society, ambience simulation, horizontal communication, citizenship, media, global audience, global consciousness.

## ABSTRACT

This article describes an idea for achieving a higher level of global visibility of certain events and for improving and stimulating citizens (in this first approach, European citizens) for a higher level of consciousness of the diversity of European reality. At present, each country or region of Europe is still living in a sort of psychological space circumscribed by the old sense of geographical border, and where information about other realities is mostly spread by means of conventional media, newspapers, magazines, TV, etc., as well as by the Internet and, in the latter case, by the information recorded by travellers. This is how the conceptions of Europe and of European citizenship are slowly developing. The proposal presented in this article, named "*HiperJanela*", aims to bring citizens to an upper level of on-time-real-information across the entire European space, by means of a global network of public video-interfaces which we call the *HiperJanelas* (notice that "*Janela*" is the Portuguese word for window).

## 1. Introduction

As a first notice, we would like to state that the idea presented in this article is to be considered anti-patent, that is, it is offered to the public by its author and anyone may implement it freely without the need for any special permission, other than a symbolic contribution in order to cover the author rights. Please contact the author at feliz@fe.up.pt, in such a case.

In these days of the *Information Society*, one of the main aspirations of the European Commission seems to be the creation not only of the institutional European space, but also of a certain European mind and citizenship (E.U., 2006). Although the European mind already exists, in its diversity, strong and well established, and based on a wisdom built along several centuries of a rich history, the visibility of such a mindset is not yet corresponding to the concept of "one-voice Europe". The weak knowledge about what is occurring in the various centres of Europe and the poor information reaching ordinary citizens are, in our point of view, obstacles to faster development. In one sense, ordinary citizens know very little about the places of other countries, how life runs in those places, how people work, what problems they face daily, and how they surmount them. Discussion and learning through comparison is therefore not stimulated. On the other hand, directives and incentives of European Union institutions hardly reach "normal" citizens, since they are usually broadcasted to the public by the media or by some country dependent institutions. Visibility of European directives, tendencies and proposals is also poor. Although such information can also be accessed via Internet, it is recognised that people often do not plan their lives based on getting constantly informed by those means, since they are fully focused in other aspects of their lives. At the same time, any polls or events that may be important for the population may well appear obstructed by regional information, since it is usually delivered by the media. This way, both the information from European institutions to the public and from the public to the European institutions is, in the present approach, deficient, mainly because there is always a third party between the two interlocutors.

Therefore, aims like those of improving Commission ability to listen, improving communication in Europe, better perception of policies, institutions, task, etc., and especially facilitating the ability to communicate with any European region, will hardly be achieved by means only of the actual network of information, where a significant quantity of information is handled through a vertical structure. In the following sections, we will expose our vision of the actual situation and confront it with a simulated ambience based on a new communicational proposal, the *HiperJanela*, which may be considered the basis of a more flexible and popular horizontal network for the improvement of European citizenship.

## 2. The present situation

As previously said, the present situation of communications among citizens and institutions in European Union (E.U.) is very much based on peer-to-peer contacts, like email, telephone, etc., and, when the information is to be broadcasted, by introducing some natural third parties between the two interlocutors . These third parties are frequently regional institutions or even regional media operators. Anyhow, the practice shows that frequently a certain obscurity is maintained in the public concerning certain events of the Union, obviously because the media cannot be fully dedicated to broadcasting such information. On the other hand, citizens are also not commonly aware of the day-to-day life in other places, and therefore have no idea of how people normally live, no way of comparing and reflecting on their own lives, in order to improve them, and get a more realistic perspective of our common space. Figure 1 aims to represent the actual type of system, in terms of information sharing. In a certain sense, Europe at present still is a universe made up of several domains which are still very enclosed. We believe that this is an obvious obstruction to the intellectual perception of the whole and, therefore, also an obstruction to the evolution of a superior state of awareness.

In figure 1, these *domains* are schematically represented. Peer-to-peer communications are shown in the form of *dashed* links, and broadcasts in terms of *solid* lines. The E.U. institutions use these two types of approaches to interface with citizens. Third parties, as depicted in the figure, which in many cases operate with other objectives than solely to inform people, are usually responsible for broadcasting.

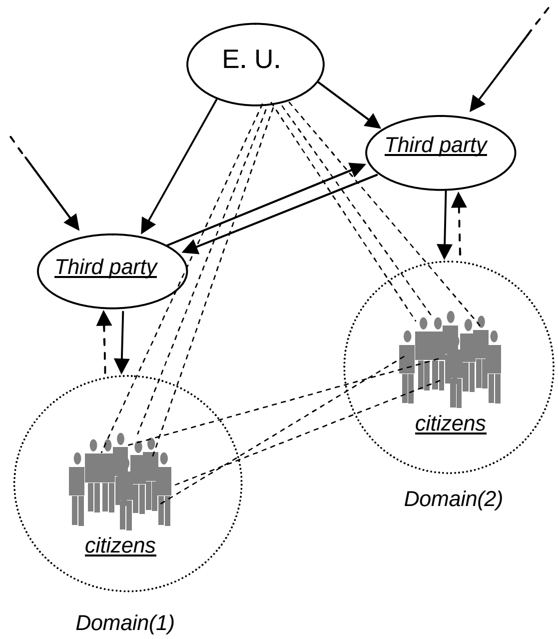


**Fig. 1** Actual communication structure in the E.U.

A conclusion that can easily be drawn from this scheme is that citizens will be only informed (1) by what third parties deliver; (2) by informing themselves directly at the European Union Internet sites and institutions, or (3) by what the community of people will share by email, telephone, chat, etc. This is obviously a system which is not only far from being optimized but also susceptible to generating information noise. As we said, we claim that this is extremely obstructive to faster and cleaner development of European citizenship.

## 3. The *HiperJanelas* communication space

The prime aim of the *HiperJanela* concept is to make the communication of different realities in an extensive geographical space as reliable and horizontal as possible. In a sphere where visibility, flexibility, trust and reliability are key words for the development of a progressive society, this aim is appropriate. The *HiperJanela* space must therefore allow the following: (1) information from E.U. will reach the citizens directly, and without being filtered or delayed by third parties; (2) citizens will be able to have an on-time real visual perception of life running in diverse locations of the Union, by simply looking through the windows; (3) citizens will be free to use such visual information for becoming more aware of events, proposals and possibilities, and even for personal contact with other members of the community.

In our view, this may be achieved by installing high resolution video-interfaces between the various domains belonging to the E.U. space. As suggested in the scheme of figure 2, each *HiperJanela* installed between domains *i* and *j* ($HJ_{ij}$) will ensure the exchange of an on-time video of the two realities to their citizens. Citizens *i* will literally have a view on the universe *j* and vice versa. In effect, people would then have the possibility of *looking into* the other side and observe, learn and communicate through the *HiperJanela*.

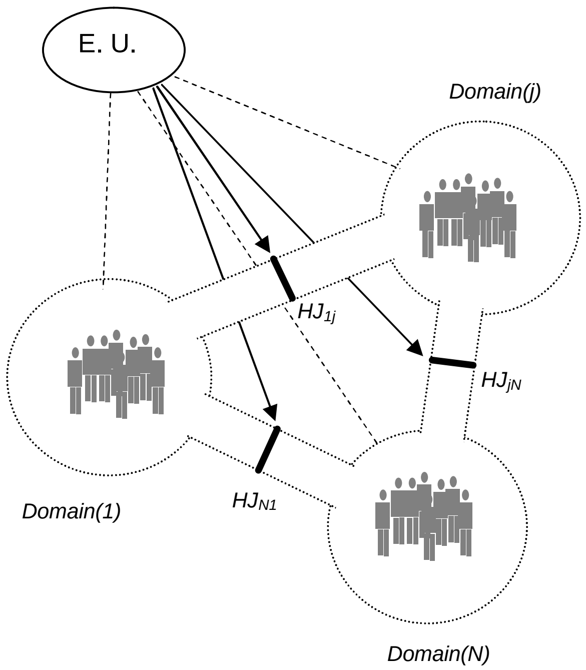


**Fig. 2** Proposed structure using *HiperJanelas* (HJ)

At the same time, E.U. institutions will be now able to deliver specific information to a specific domain or even use these windows to directly broadcast information for all. The citizens' feedback can therefore be pumped up and simply completed by accessing the sites on the Internet proposed in the window, for more detailed information or actions. This scheme, which does not have to eliminate third parties from the process, but instead reduce their charge, establishes a direct feedback between citizens-citizens and citizens-E.U.

It is obviously not practical to maintain a link to each domain in all the domains at the same time, however, it is perfectly possible to commute these links after a certain period of time in order that all the domains can be scanned and become visible. The system is therefore a sort of rotating presentation of pairs of video-images, through which people will slowly get to know and develop a stronger sense of community. A *HiperJanela* in Nuremberg can, for instance, be connected during a week to Porto, and then be commuted to Madrid and stay there for the next week, for example. At the same time, other *HiperJanelas* installed in the European space would be operating in the same manner, giving people a better sense of how life runs in the overall communitarian space, while letting E.U. institutions achieve an excellent efficiency on broadcasting information.

## 4. A simple *HiperJanela* system

It is possible that this kind of space can be implemented in various ways, but here we propose a system which is very simple and reliable. It is based on a simple *video-panel*, perhaps made of several plan TV screens, to which a digital video-camera system is adapted. The images from the *Domain(i)* are captured by the camera $C_i$ and then transmitted to the *Domain(j)*, and vice versa, at the same time, as represented in figure 3.

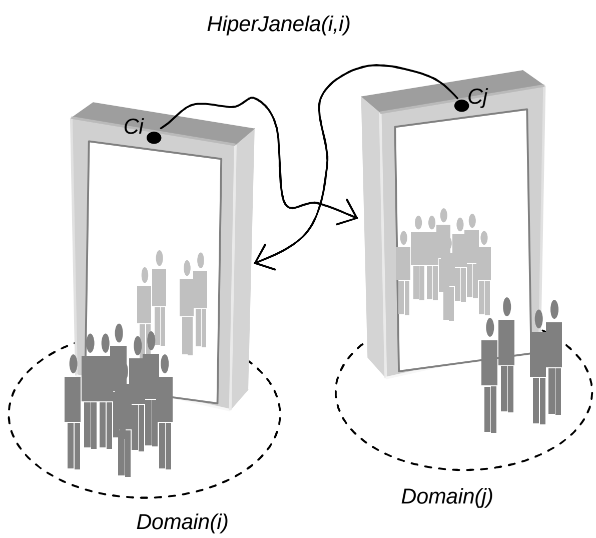


**Fig. 3** The *HiperJanela* system

As we now see, at the very same moment that people can be informed about E.U. by some text messages presented over the image, in the form of running banners, or in a corner of the panel, for example, people can also *look into* the other side and say greet other people, or even communicate other messages visually, almost instantaneously. Friends, for instance, may sometimes meet at the *HiperJanelas* and send fast messages, arranging meetings, exchanging numbers or sentences written in a paper, and so on. People will learn to use this resource as they require, while developing their own creativity. The sense of a common space will quickly emerge as an upper dimension of our *Information Society*. Politically, there will be also many advantages for the democracy, since the visibility of the diverse realities will be tremendous, and the information shared almost free of noise. This can be done either by fast Internet connections or by using satellite communications, for example. And people will simply feel the diverse reality in which they are living in. The following simulated images aim to give a better idea about what can be achieved by means of the implementation of such a concept.

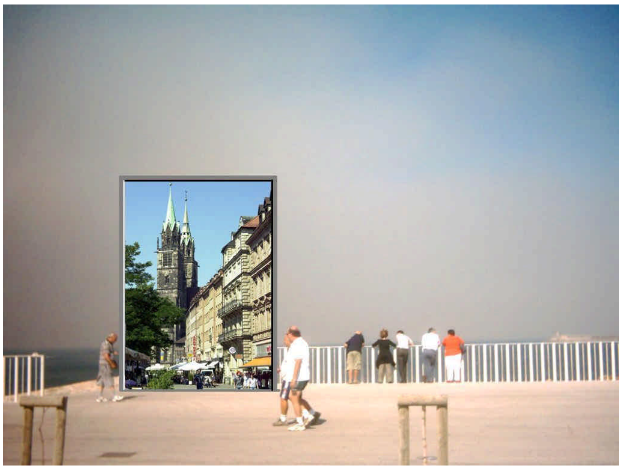

**Fig. 4** *HiperJanela* between a street of Nuremberg, Germany, and a location near the sea in Porto, Portugal

Notice that the *HiperJanela* dimensions can also be diverse, and therefore these tools will be easily adaptable to the spaces where they are to be installed. A *HiperJanela* can be simply installed as a panel in a plaza or in a street, or inserted in the space of a real door or window of a building, in a café, for example. This, of course, already gives an idea of the powerful vehicle of information contained in the *HiperJanela*. Technologically, it is a concept that presents no challenges for the actual information technology, and, at the same time, the tendency will be to improve the quality of its images as time passes and technology develops even more.

**Fig. 5** *HiperJanela* installed at a corner of a building of *Maximilianstrasse*, in München, Germany


**Fig. 6** *HiperJanela* installed in a street of Porto connected to *Marienplatz*, München, Germany

**Fig. 7** *HiperJanela* installed at the *Plaza Mayor* of Madrid, Spain

The most interesting aspect of this proposal, however, is that it introduces such a high level of information on many levels of citizens' lives. In effect, one can imagine an esplanade of Lisbon linked to an esplanade of Vienna; a metro station of

Paris linked to a metro station of Napoli; a public café in Brussels linked to a public café in Roma or Barcelona, etc. The ability to join all these ambiences while broadcasting the messages (or some small images) from the E.U. institutions to all of them is the precious potential of this system.

## 5. *HiperJanelas* and Arts

As another interesting curiosity of this system, we would like to point out the effects that can be achieved by arts in these windows, which can even make each *HiperJanela* a sort of attractive touristic element.

**Fig. 8** *HiperJanela* bordered by an Arabic door


**Fig. 9** *HiperJanela* with a running banner moulded by a Portuguese door with *azulejos*

In figure 8, is simulated a *HiperJanela* of Andaluzia connected to a surface tram somewhere in another location in Europe. On the other hand, in figure 9, a *HiperJanela* enclosed in a Portuguese door with *azulejos*, with messages passing in a running banner, is linked to a view on the Plaza Mayor of Madrid.

## 6. *HiperJanela* operators and advertisement

Finally, it is also interesting to make some considerations concerning the utilization of these windows by private operators and, consequently, for the use of advertisement. Although in our point of view the primary objective would be completely perverted if *advertising* would invade such a precious space (we expect that it will not happen), private operators could be given a little space for advertising and, therefore, for maintaining the system, as long as such advertisement would not interfere with the principle of the *HiperJanela*. In such a small space reserved to them, private operators could be induced to advertise only something related to the region or the place where the *HiperJanela* was installed. For instance, if at a certain moment the *HiperJanela* is connected to a place in Italy, then the priority would be given to the advertisement of products from that region or country, therefore improving also the visibility of regional products and tourism. This serves not only to improve the visibility of how people live, but also the visibility of each people's culture.

## 7. Conclusions

We may conclude that the *HiperJanela* concept is expected to promote and help to implement not only a direct and a horizontal information structure between citizens, but also the ability of the European institutions to quickly and reliably listen and communicate with the population. The *HiperJanela* may therefore be considered a hyper-window linking different realities across Europe and, that way, contributing to the development of a superior state of conscience and of the European mind as a whole. The importance of these windows will be even more noticed in the peripheral regions, since these are usually the last ports reached by waves of information. So, the actual peer-to-peer contacts between people and the broadcast of E.U. information through the normal media operators will be complemented by the *HiperJanela* features, which include a horizontal type of information share for connecting different people and different cultures.

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**Author Biography:**

**J. Manuel Feliz-Teixeira** graduated in Physics in the Faculty of Sciences of University of Porto, Portugal, and MSc and PhD from the Faculty of Engineering of the same university. His work has been related to various matters, from optical communications, solar energy and seismology to, more recently, the simulation of complex systems in management science, like warehouse and supply chain. His PhD thesis is on “Flexible Supply Chain Simulation”.

# Holistic Metrics, a Trial on Interpreting Complex Systems

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KEYWORDS: Complex system, holistic metrics, time domain, frequency domain, base states, state projection.

## ABSTRACT

In this article is proposed a simple method for estimating or characterize the behaviour of *complex systems*, in particular when these are being studied throughout simulation. Usual ways of treating the complex output data obtained from the activity (real or simulated) of such a kind of systems, which in many cases people classify and analyse along the *time domain*, usually the most complex perspective, is herein substituted by the idea of representing such data in the *frequency domain*, somehow like what is commonly done in *Fourier Analysis* and in *Quantum Mechanics*. This is expected to give the analyst a more holistic perspective on the system's behaviour, as well as letting him/her choose almost freely the *complex states* in which such behaviour is to be *projected*. We hope this will lead to simpler processes in characterizing complex systems.

## 1. **Introduction**

There are presently very few notes on the kind of metrics that could be reliable and of practical relevance when applied to the interpretation of complex systems behaviour. These systems are often based on intricate structures where a high number of entities interact with each other. Metrics are there for appropriately characterizing the nodes or individual parts of such structures, or small groups of them, but when the intent is a measure for the complete structure either they fail or appear to be too simplistic. That is certainly a good reason for modelling those cases using a *strategic* point of view, removing the *time* variable from the process, as in doing so the complexity is reduced *a priori*.

But when a dynamic and detailed representation is essential, the interpretation of the results and the characterization of the system frequently fail. This issue seems sometimes also related to a certain tendency impregnated in the minds to look at the systems from a pre-established perspective. At this point, however, perhaps this may be considered a conflict between different scientific approaches: the classical western reductionism, of anglo-saxonic inspiration, which believes the best approach is to break the system into small parts and understand, model or control those parts separately and then join them together, therefore looking at the world in an individualist way; and a more holistic approach, a vision slowly spreading and largely inspired by oriental cultures, which considers that each part of the system must be seen together with the whole and not in isolation, and therefore locates the tone in how the interactions between such parts contribute to the whole behaviour. Hopp & Spearman (2001, pp.16), for instance, comment about this saying that "*too much emphasis on individual components can lead to a loss of perspective for the overall system*".

A significant number of authors defend this opinion, pointing out the importance of developing a more holistic point of view to interpret and study systems behaviour, in a way that analyses maintain enough fidelity to the system as a whole. As

Tranouez et al. (2003), who apply simulation to ecosystems, would say: a complex system is more than the simple collection of its elements.

In management science, for instance, the "western" approach frequently generates difficulties at the *interfaces* between elements, typically of inventory or communication type. On the other hand, as *just-in-time* (JIT) systems give better emphasis to the relations and interactions and are continuously improving, the overall movements tend to be more harmonious. JIT already looks at systems in a certain *holistic* way. The same seems to be true in regard to other fields where simulation is applied, and mainly when the number of states to simulate is high.

## 2. **Holist measuring (a proposal)**

But, what concerning metrics? How can one measure such a high number of states typically found in complex systems in order to effectively retrieve from them some sort of useful information?

As a metric is a *characterization*, we could think that maybe the modern *Data Mining* (DM) techniques could be extensively applied, for instance. These techniques use decision trees and other algorithms to discover hidden patterns in huge amounts of data, and are nowadays applied to almost any problem based on extensive data records, for instance, in *e-Commerce* for customer profile monitoring, in genetics research, in fraud detection, credit risk analysis, etc., and even for suspected "terrorist" detection (see Edelstein, 2001; Edelstein, 2003). However, they often imply the usage of high performance computers, sometimes with parallel processors, as well as huge computational resources to analyse *GBytes* or even *TBytes* of data. They are useful when any single record of data can be precious for the future result, and thus when all data *must* be analysed.

On the other hand, in many practical simulations a significant amount of data is not significant for the final conclusions, the simulation process is in itself a filter, and therefore such data may well be ignored in the outputs, even if it could have been essential to ensure the detailed simulation process to run. In the perspective of the author, maybe there is a way that could deserve some attention: the idea is to filter such data during the simulation execution and, at the same time, to turn the measures probabilistic by using an approach somehow inspired by the *Fourier Analysis* and the *Quantum Mechanics*. That is, to represent the overall *system state* ($\psi$) in terms of certain *base functions* ($\psi_i$), and then to measure the *probabilities* ($\alpha_i$) associated with each of these functions. The interesting aspect of this is that each base state function ($\psi_i$) could even be arbitrarily chosen by the analyst, and the probabilities ($\alpha_i$) easily computed during the simulation process. Final results would then be summarised in some expression of the form:

$$\psi = \alpha_1 \psi_1 + \alpha_2 \psi_2 + \ldots \alpha_j \psi_j + \ldots \alpha_n \psi_n \qquad (1)$$

which could be interpreted as: there is a probability of $\alpha_1$ that the system will be found in the state $\psi_1$, a probability of $\alpha_2$ that the system will be found in the state $\psi_2$, etc. This would be the final measure of the system, in a sort of characterization of expectations under certain conditions. This also corresponds to *projecting* the system behaviour into the generalised vectors base of *state functions* ($\psi_i$). The amounts $\alpha_i$ simply correspond to the values of those projections.

In *Fourier Analysis*, for instance, the complex behaviour observed in the *time axis* (see the example of figure 1) is substituted by the decomposition of such a signal into *sine* and *cosine* mathematical functions, and that way transferred to the *frequency* domain.

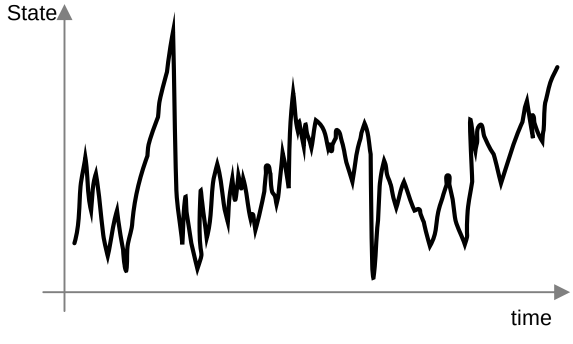


**Fig. 1** Example of a general complex signal

The result is that the analyst is now much more able to visualize and to interpret the complexity of the previous signal, since it is as if this signal would be now expressed in terms of *patterns* (see example of figure 2). What firstly appeared as a confusing and almost randomly up-and-down behaviour may now be simply understood as the summation of some sinusoidal patterns with different amplitudes. *Quantum Mechanics* uses a similar formalism. We believe that the method proposed here will help generating such a clean view also when applied to the behaviour of *complex systems*.

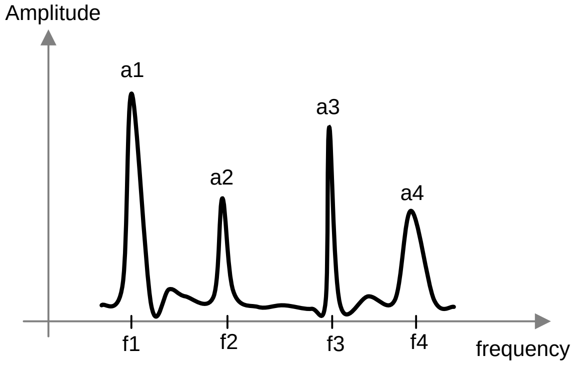


**Fig. 2** Typical signal in the frequency domain

The present proposal may also be understood as an attempt to represent the system behaviour in terms of a sort of generalised histogram, where the *categories* are the functions $\psi_i$, which may correspond to the frequencies $f_i$ in the previous figure, and the probabilities $\alpha_j$ are made to correspond to the amplitudes $a_j$ in the same figure. In terms of this figure, the analyst would recognize a probability of $a_1$ that the system would be found in the state $f_1$, a probability of $a_2$ that the system would be found in the state $f_2$, etc.

## 3. An imaginary example

To help explain this, we can imagine a complex system like the Supply Chain shown in figure 3, for example.

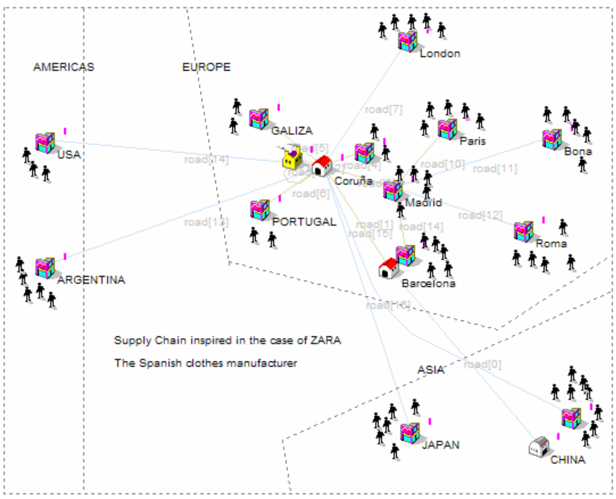


**Fig. 3** Imaginary Supply Chain inspired by ZARA

This is an example inspired by the company ZARA, the trendy Spanish clothes manufacturer of La Coruña. This company, from the INDITEX group, is worldwide known as a paradigm of success, despite its owner, and major manager, Mr Ortega, the second richest person in Spain, refusing several conventional practices claimed by most schools of management. ZARA refuses, for instance, the idea of advertisement. Forgive me if indirectly I am advertising it here.

Returning to our subject, how can we apply our concept of holistic metrics to retrieve some useful information from such a complex case[1]? How can we specify the *base functions* (or *base states*) in which the system's behaviour will be *projected*? How will we calculate and represent the respective projections?

First of all, we have to choose the $\psi_i$ functions into which the measures will be *projected*. We may choose them in terms of some specific *conditions* related to the information that must be obtained from the system. For example, if Mr Ortega is concerned about the levels of *stockouts*, *holding costs*, *service level*, *turnover*, etc., which are typical measures of Supply Chain Management, he may for example define some sort of base functions by using conditions of the type:

$\psi_1$ – *Stockouts above 7%*
$\psi_2$ – *Holding costs above 5%*
$\psi_3$ – *Service level under 75%*
$\psi_4$ – *Turnover under 2*

Then, while the system is running, it must be *projected* into these set of functions, that is, the occurrences of each of these conditions must be counted up, whenever they are true.

Supposing $n_j$ the accumulated number of occurrences of the condition $\psi_j$, and $N_j$ the total number of its samples, an estimation of $\alpha_j$ can simply be computed as:

$$\alpha_j = n_j / N_j \qquad (2)$$

And the overall system state will therefore be expressed as:

$$\psi = (n_1/N_1)\psi_1 + (n_2/N_2)\psi_2 + (n_3/N_3)\psi_3 + (n_4/N_4)\psi_4 \qquad (3)$$

Notice that, in general, *base functions* are

[1] In this figure is represented less than perhaps 10% of the real ZARA global Supply Chain structure.

chosen to be orthogonal, or independent of each other, but in fact that is not a *must* for using this type of representation. One can also *project* a system into *non orthogonal* axis. As we said previously, such a measure may be seen as a characterization of expectations under certain conditions. The overall system state is, in reality, represented by the following weighted equation:

$\alpha_1$ *(Stockouts above 7%)* + $\alpha_2$ *(Holding costs above 5%)* + $\alpha_3$ *(Service level under 75%)* + $\alpha_4$ *(Turnover under 2)* (4)

Now, if we build a histogram out of this data, we will *characterize* the system by means of a probabilistic graphical format, obtaining something of the type:

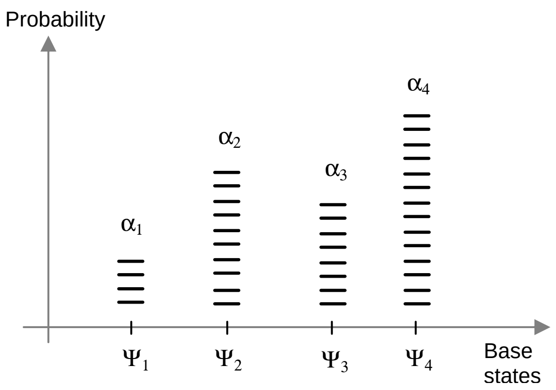


**Fig. 4** Characterization of the system's behaviour

Were the probabilities are the $\alpha_i$.

So, once the *base states* are well defined by the analyst, the characterization of the system is possible, no matters how complex the system is. We recall that in many practical cases the analyst is mainly focused in being sure that certain variables of the model do not cross some upper or lower limits, or, if they do, with which probability it happens.

In order to evaluate the system in a wider range of modes of behaviour, several studies of this kind can be made with the system operating in different conditions. That will make possible to improve the knowledge about the system, or its characterization.

The former example was taken from a typical Supply Chain problem (see Feliz-Teixeira, 2006, pp. 222), but this technique can be applied in general to other complex systems. For example, in a traffic system of a town, the *complex states* could be chosen to be the number of cars exceeding a certain value in a certain region, the travel time exceeding a certain value in another region, the number of public vehicles reaching a certain zone inferior to the minimum required, etc. As we recommend that these base functions (or *complex base states*) be well defined before simulation takes place, it implies that the simulation objectives must be well known prior to the start of the simulation process. Not always this is possible, of course, since simulation can be used to detect anomalous situations not predictable by means of other methods, for example.

This technique may, however, be also used as a method for analyse any sort of results, by being directly applied to the raw outputs of the complex system. In that case, the simulation will be a standard process and all the work is done by data manipulation. The results, in principle, will be the same, but that approach will in general be much more time consuming.

Finally, we would like to emphasise that we use the term "*holistic metric*" for distinguishing this kind of approach from those approaches which usually characterize systems by means of *averages* and *standard deviations* taken over a certain number of variables (usually a high number). These, as we know, frequently confuse the analyst's mind with the complexity of the results, instead of allowing a useful interpretation of the system's behaviour. Quantity of information is not all, and sometimes it can even generate confusion instead of clarity, if it is in excess. Besides, the method presented here goes on the trend of the "holistic" mind that seems to emerge in our days, as we defend.

## 4. CONCLUSIONS

Complex results generated by a *complex system* are very much dependent on how the analyst looks at the system and on how such results are analysed. We would say that any complex system can be minimally understood as long as the analyst knows what to search for, that is, if the objectives of the study are previously defined. This is because such objectives can in reality be used to establish the *base functions* (vectors) of an imaginary space where the complex behaviour will be *projected*, that way giving an automatic meaning to the results.

This may also be seen as an attempt to measure the outputs of systems in the *frequency domain* (as in *Fourier Analysis* and in *Quantum Mechanics*), instead of in the *time domain* where signals usually are more difficult to interpret. Although no practical cases have yet been studied based on the idea presented in this article, we expect to use and test this approach in our next studies of simulation. We would also be pleased with receiving some feedback from anyone who decided to apply the same logic.

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# Comparing a Standard and a Naïve Stock Refill Policies by Means of Simulation

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## ABSTRACT

In this paper will be compared, by means of a next event dynamic simulation, two different stock refill policies applied to the same in-lined one-product Supply Chain. The first method is the Japanese method usually known as KANBAN[1] (similar to the "*Two Bins*" method, in terms of dynamics), and the second is a naïve method named by the authors the "*BanKan*" for the reasons that will be explained later in this text. The surprising results obtained show an obvious operational advantage of the naïve method, at least under the conditions of the present Supply Chain design and configuration. This method does not make use of any criteria dependent on the actual stock level at the facility, and it was also observed that the materials flow through the Supply Chain as in a "river without dams", and with extremely low local inventory, as it was defended by Taiichi Ohno, the father of *just-in-time* (JIT) systems, in the 1980s.


## 1. Introduction

This article is the result of a curiosity: the curiosity of taking to confrontation the sophisticated and the obvious. The idea was first coming out as an example to help to test and verify the consistence of a Supply Chain Simulator conceived by Feliz-Teixeira in his Ph.D. studies (Feliz-Teixeira & Brito, 2003) and inspired by the vision of materials flow presented by Mr. Taiichi Ohno for the Toyota Production System (Ohno, 1988), which have resulted in the KANBAN system to implement JIT. Contrary to the occidental believes of those times, which were based on demand forecasts and have leaded to *just-in-case* (JIC) systems using a *push*-into-stock philosophy, the KANBAN method had changed the sophisticated forecasts by the simpler idea of producing the smallest possible quantities of material triggered by the real demand, thus *pulling* the materials from the stock. Systems of this kind let the Japanese automotive industry overcome its American counterpart already in the turn of 1980s, for example, and since then have started to be applied in many other industrial areas all over the world, whenever is possible. We have chosen this method as the standard method because of its simplicity and for its excellent performances. Nevertheless, the KANBAN system is still using Bins of material, and decides the moment to ask for the next Bins based on the quantity that rests in the stock after each stock operation. This method will be carefully explained in the next section. By the contrary, the naïve method does not need any information about material levels in the Bins to order the new material. Thus, it is completely independent on the inventory state.

It is also important to notice that the simplicity of KANBAN systems could help reduce dramatically the inventories as well as improve the throughputs, and in fact the materials flow close to the flow of a river, but, as we will see, the naïve method is even more effective in inventory reduction and, unlike the KANBAN that flows like a river by impulses, the naïve *BanKan* will simply flow continuously.

## 2. Overview on the KANBAN (*Two Bins*) method

Originally, the KANBAN method was used to ensure the perfect availability of materials at the input of a work-station in a production system, but later it started to be used also as a material reordering policy between facilities in certain Supply Chains. *Volkswagen*, for example, is today applying JIT concepts in the supply network for the production of its new *Beetle* model, between Martorell, Spain, and Puebla, Mexico. But a better understanding of the KANBAN method can be achieved with the help of the next figure (Fig.1).

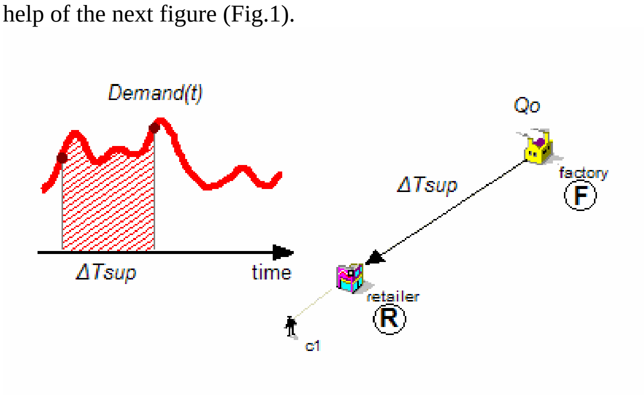


**Fig. 1** Factory serving a retailer

Let us consider a factory (F) producing a previously optimized lot size (*Qo*) of a certain product, and needing a time $\Delta T_{sup}$ to supply the retailer (R), in which there is a time dependent demand *Demand(t)*. Following the simple idea of the "*Two Bins*" method,

[1] In fact, the KANBAN is a signal to authorize the production of the next Bin of material, and it is many times associated with a card.

the minimal quantity the retailer (R) must order to the factory to avoid *stockouts* is the total demand during $\Delta T_{\sup}$, that is, the total demand during the time the new material will need to arrive from the factory. As one can see from the figure, this quantity can simply be given by the integration:

$$\int_{to}^{to+\Delta T \sup} Demand(t).dt \qquad (1)$$

As this quantity is in most of the cases dependent on both *to* and $\Delta T_{\sup}$, this integral is usually approached in practice by an estimation of its value calculated from historical data, known as the *Demand During Lead-Time* (*DLT*), plus a safety-stock quantity (*SS*) which is expected to protect the system against variations in the real *Demand(t)*. Thus, the minimal quantity to order to the factory will be:

$$DLT + SS \qquad (2)$$

Or, expressed in terms of factory lot sizes (*Qo*):

$$Ko = \frac{DLT + SS}{Qo} \qquad (3)$$

*Ko* is therefore the minimum number of lots to order to the factory, is usually known as the KANBAN, and can in practice be signalled by a card located at the appropriate position of the stock, as figure 2 suggests. Each time the inventory level reaches the KANBAN there must be a new order of material.

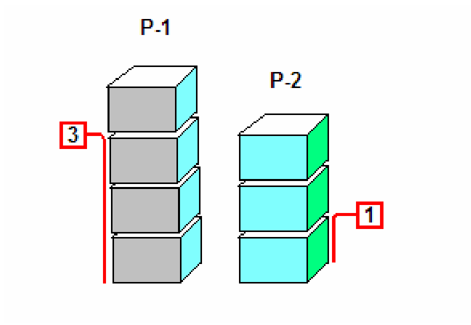


**Fig. 2** Using KANBANs to signal reorder points in a stock of two products

Notice that if the factory lot size (*Qo*) would match the *Demand During Lead-Time* (*DLT*), then *Ko* = 1, and this case would automatically transform in the widely known "*Two Bins*" method, which uses two Bins of material and decides the moment to ask for the next Bin based on the quantity that rests in the present Bin. The full Bin quantity is established to represent the *Demand During Lead-Time* (*DLT*), and a new Bin of material is ordered whenever the present Bin gets empty (or almost).

## 3. The in-line one-product Supply Chain

Imagine now that the factory and the retailer become simply too distant for that the KANBAN quantity at the retailer can be maintained within acceptable values – for instance, in accordance with the *Economical Order Quantity* (EOQ) of Ford W. Harris (1913) –, and thus there is the need to order the material to an intermediate warehouse. For academic purposes, let us consider this new warehouse located precisely at a Lead-Time distance of $\Delta T_{\sup}$, and that it will order the material to a second warehouse distant of $2\,\Delta T_{\sup}$, and finally that this second warehouse will order the material to the factory distant of $3\,\Delta T_{\sup}$, as it is depicted in the figure 3. It is considered only one product. This kind of lineal Supply Chains is many times used for didactic or academic purposes, as it is, for example, the case of the so called "*Beer Game*" developed at MIT in the 1960s (Sterman, 1989).

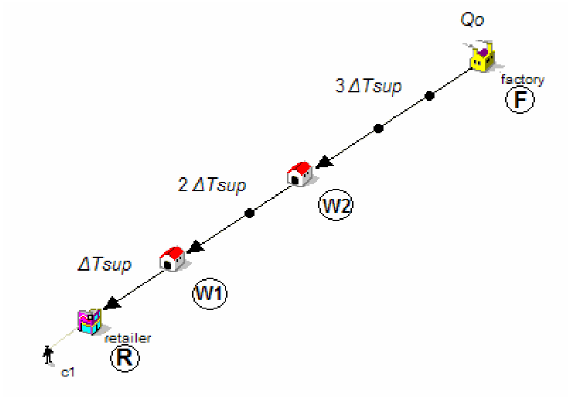


**Fig. 3** In-line Supply Chain to compare the KANBAN and the *BanKan*

In this case, the objective is to compare the KANBAN method with the naïve method that soon will be presented. With such intents and for simplicity, let us consider the lot size (*Qo*) matching the *Demand During Lead-Time* (*DLT*) on the retailer. Then, it comes out from the examination of last figure that *Ko* = 1 for the retailer, meaning the retailer must order a Bin = *Qo* to the first warehouse (W1) each time the actual Bin gets empty (or near empty). Then, this warehouse will order to the second warehouse (W2) a quantity *2Qo* each time its stock reaches the KANBAN *Ko* = 2, and this facility will finally order to the factory a quantity *3Qo* whenever its inventory level reaches the KANBAN *Ko* = 3. Notice that this differences result from different *Demand During Lead-Time* (*DLT*) values observed along the Supply Chain.

## 4. Simulating the case

This Supply Chain have been modelled using a Supply Chain Simulator created by Feliz-Teixeira during his Ph.D. studies (Feliz-Teixeira & Brito, 2003), and the results have been achieved with the same simulation tool.

In the case under study, the customer's demand have been defined as *d* = 1 product units per day, with a standard deviation of 0.3 days. This let us choose *Qo* = 10. On the other hand, the *Time for Full Satisfaction (TFS)* of the customer was established to be 0.3 days, what means any order arriving from the retailer within this delay will be considered 100% satisfaction[2]. Orders with longer delays will contribute to the decline of the customer's satisfaction.

Concerning the retailer (R), whose reordering policy and configuration was kept the same in the two simulated approaches, the initial stock was 12 units, the stock refill policy was the KANBAN (*Ko* = 1), and it was allowed *no-backorders*. On all the other facilities *backorders* were allowed. All the other facilities used in the first approach the KANBAN method for reordering material, as it was explicitly referred in the last section, and only in the second approach they used the *naïve method*. The retailer, as we have noticed, kept using the KANBAN in the two cases.

Finally, it have been assumed $\Delta T_{\sup}$ = 10 days. So, the first warehouse (W1) will be distant from the retailer 10 days, as well

[2] We use this measure to retrieve a quantitative idea on the clients "satisfaction", and we apply this concept not only to last customers but also to any facility in the supply chain.

as 20 days from the second warehouse (W2), which will be 30 days distant from the factory (F). The factory is served by an ideal supplier distant 40 days.

The final results were obtained applying statistics to the data acquired after 5 simulation replications of the same model, with each run representing one year of operations. The measures of interest for each facility were the *inventory state*, the *accumulated variable costs*, the "*satisfaction*" as defined above, and finally a group of standard metrics usually applied in Supply Chain facilities[3], like the *total costs*, *variable costs*, *incomes*, *turnover*, *service level*, and *stockout ratio*. It was based on this measures that the two refill policies have been compared.

### 4.1 *Results with the KANBAN policy*

As we have noticed before, in any case the retailer was operating with the KANBAN method and for that reason some of the results related with this facility will be very similar in the two cases in study. An example is the *inventory state*, which is shown in the next figure (Fig. 4). As one can see, the inventory starts from the initial condition of 12 units and swings as expected between 0 – 12 units.

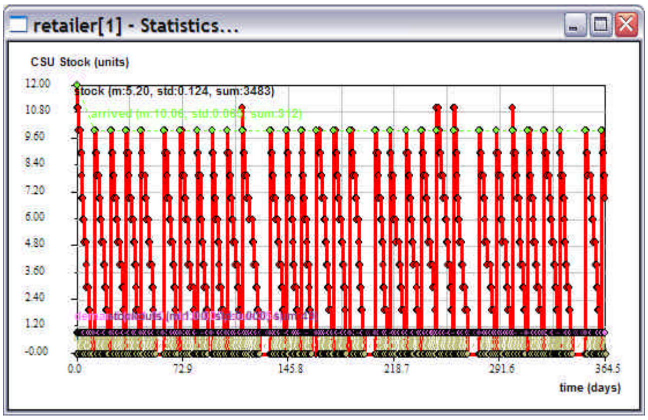


**Fig. 4** Retailer inventory state during a year of simulated operations

Another similarity of the two systems is the customer "satisfaction", depicted in the figure 5, which runs oscillating between 50% and near 100%. Remember this holds for a *Time for Full Satisfaction (TFS)* in the customer of 0.3 days. Notice also that there is some orders "*not served*", which correspond to *stockouts* at the retailer.

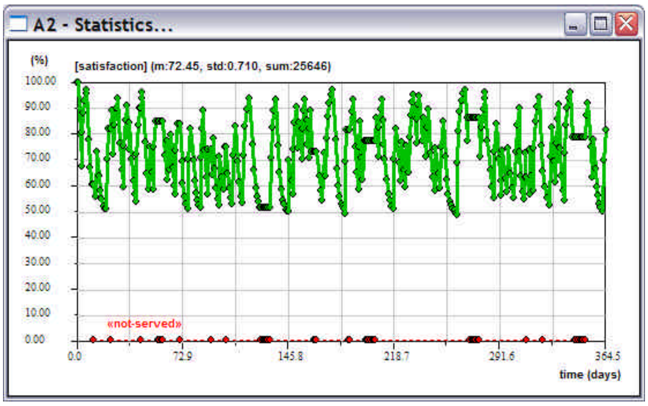


**Fig. 5** Customer's "*satisfaction*" and "*not served*" orders

As we will see later, the big differences will be noticed on the other measures and more dramatically at the upper facilities on the Supply Chain. For the purpose to compare with next results, we show in the figure 6 the inventory state of the second warehouse (W2). By inspecting this figure is easy to detect that the KANBAN was *Ko* = 3, once it always orders 30 units of material. The inventory level swings between 0 – 40 units.

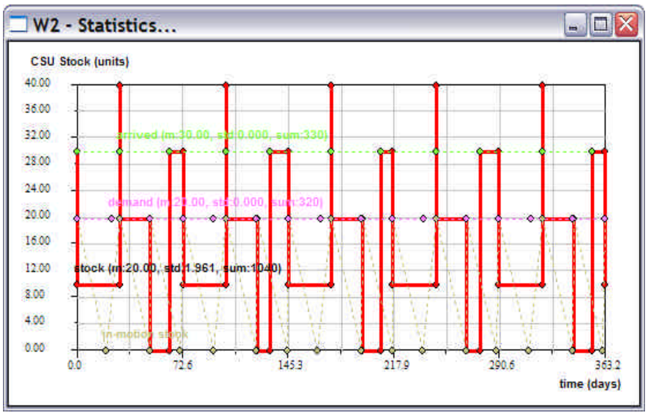


**Fig. 6** Warehouse (W2) inventory state during the simulation

It have been observed that the first warehouse (W1) and the factory exhibit this same kind of swing, the first between 0 – 20 units and the last between 0 – 60 units.

Finally, on the next figure (Fig. 7) is represented the final characterization of the retailer (R) performance in terms of some standard logistic measures, considering also their variability along the 5 simulation runs.

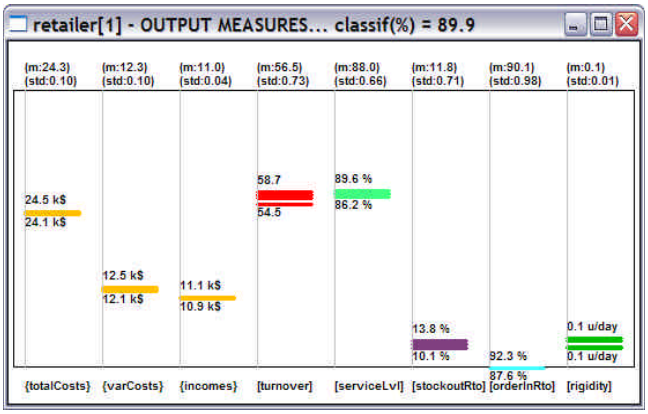


**Fig. 7** Retailer final characterization

Notice that the *turnover* was around 56, the *service level* around 88% and the *stockout ratio* of the order of 12%. The last measure is not standard, is still in study, but it is expected to make possible the measure of "*rigidity*" at the facility, which is thought as the inverse of "*flexibility*" (Feliz-Teixeira & Brito, 2004). These results seem plausible to be expected on a JIT system.

### 4.2 *The naïve BanKan and its results*

It is now time to break the secrecy and talk about the naïve *BanKan* method. It is always difficult to start talking of a naïve solution, but we hope most of this strange impression will vanish after the presentation of the results achieved with such a scheme.

If we imagine a river, it is easy to understand that the material is moving by the influence of vacuum. That is, as long as a certain quantity of material leaves a certain space, the same amount of material is automatically moved to that space in order to fulfil

[3] Even if some efforts are being made to establish Supply Chain metrics (Lambert & Pohlen, 2001), meaningful metrics that look to the network structure of a Supply Chain are not yet precisely defined. Most of the times people still talking about and apply standard logistics measures.

such vacuum. Obviously, this process does not have anything to do with the quantity of material in motion, but only with an action that is triggered by another action. If in a certain moment 10 litres of water are moving forward, it automatically will be moved 10 litres of water to that same place in order to maintain the coherence of the fluid. If, in another situation, de quantity that leaves is 23, for example, then the quantity that enters must be the same 23. There is, in fact, no need of any other reasoning or calculation. On the other hand, if the water stops in one place, all the other "places" will stop as long as they are completed of water. To better visualize this process in a Supply Chain helps consider the water having a very high viscosity, thus moving very slow each time it has to fulfil a certain "emptied" space. Also, it can help to think on a chain of men unloading rice bags from a truck. Each man passes a bag to the next man as long as there is a "vacuum" in the next man and material enough to fulfil such "vacuum".

From these considerations the naive policy comes out as saying: "*I will order whenever someone orders me, and exactly the same quantity*".

Let us make a pause for laugh, but also to look once more at the Supply Chain in study, which is presented again in the next figure (Fig. 8).

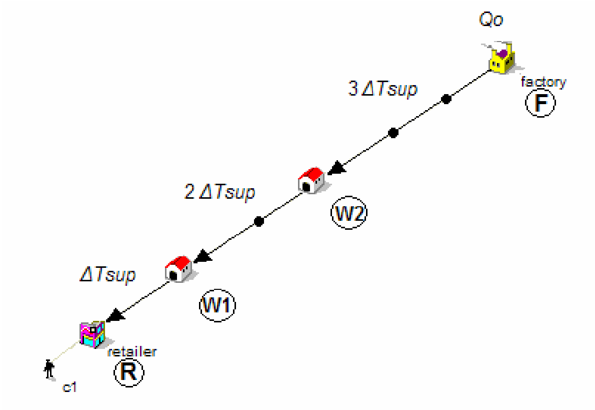


**Fig. 8** In-line Supply Chain to compare the KANBAN and the *BanKan*

Taking in account that the retailer must always use the KANBAN, it will order *Qo* to W1. If now all the other facilities use the naïve method, in that precise moment W1 orders *Qo* to W2, and this the same quantity to the factory, and the factory to its supplier. At the same time, a quantity *Qo* is served to each client facility if there is stock available. As it is now easier to visualize, the quantity of material that will flow between any of the facilities in the Supply Chain is always *Qo*, the lot size produced at the factory which matches the *Demand During Lead-Time* (*DLT*) at the retailer, as previously considered in the section 3. The result is a continuous flow of material from the factory to the retailer, precisely like in a river free of dams. Of course, to ensure there will be no *stockouts* during the start and any restarts of this process one must ensure a certain minimum inventory at the beginning at each facility. And this minimum inventory is precisely the previous value of the KANBAN at the facility. That is, the first warehouse (W1) must have an initial stock of *2Qo*, the second warehouse (W2) an initial stock of *3Qo*, and the factory (F) an initial stock of *4Qo*.

Let us now present some results obtained with this method. The next figure (Fig. 9) represents the *inventory state* again at the retailer (R), and, as we have predicted, it is very similar to that of the last case. The initial stock is again 12 units, and during one year of simulated operation it was swinging between 0 – 12 units. It is observed, anyhow, that the retailer incurred in less *stockouts* than in the previous case, as we will see soon.

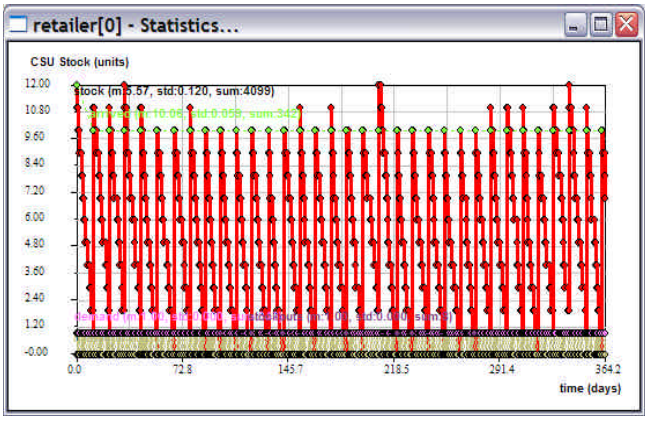


**Fig. 9** Retailer inventory during a year of simulated operation

Depicted in the figure 10, it is the customer "*satisfaction*" which again oscillates between 50% and near 100%, as in the previous case. Nevertheless, it can also be observed from this figure that there was much less cases of material "*not served*" to the customer, which obviously means less *stockouts* at the retailer.

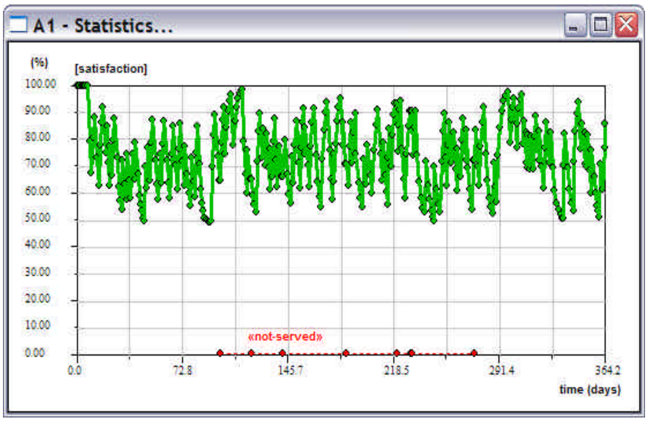


**Fig. 10** Customer's "*satisfaction*" and "*not served*" orders

The figure 11 shows the inventory at the second warehouse (W2), which must be compared with the previously shown in figure 6. The initial state is *3Qo* = 30 units, but then the level goes fast down to the range 0 – 10 units. This is because the naïve method tends to turn the inventory practically all into motion.

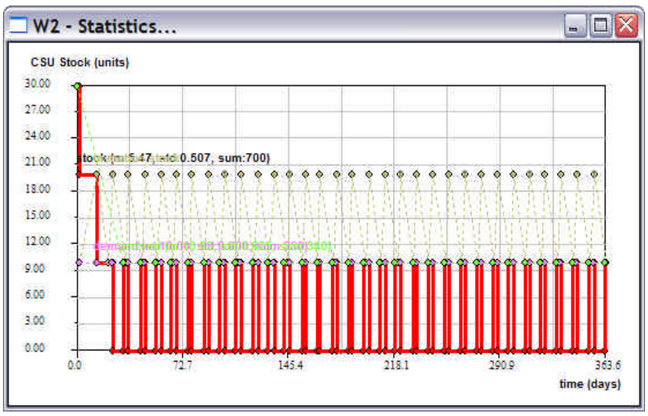


**Fig. 11** Warehouse (W2) inventory during the simulation

This same behaviour have been observed at the other facilities (except the retailer), and the next figure (Fig. 12) shows the inventory state at the factory (F). Once again the initial stock of 40 units was fast going down to the range 0 – 10 units, which is precisely the range observed at any of the warehouses.

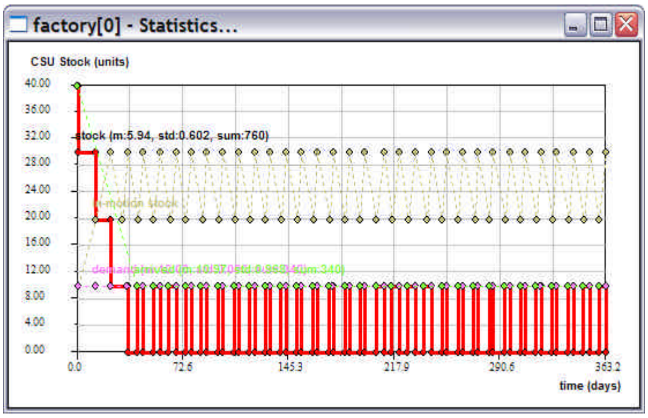


**Fig. 12** Factory (F) inventory during the simulation

Finally, on the next figure (Fig. 13) is presented the final characterization of the performance of the retailer (R) in terms of the same standard logistic measures as before, considering also their variability along the 5 simulation runs.

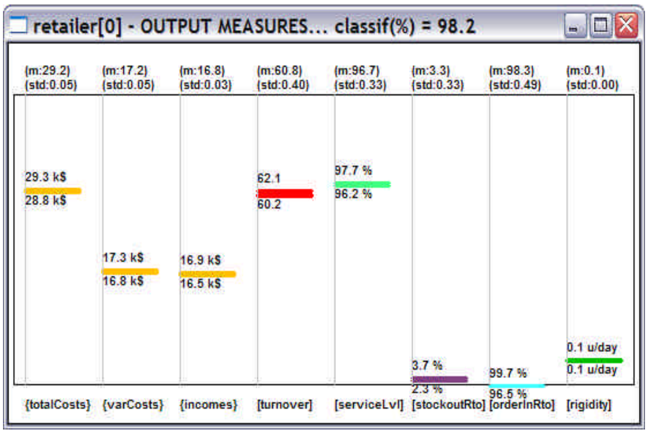


**Fig. 13** Final characterization of the retailer

From these measures, which must be compared with those of figure 7, one can already conclude about the superior operational performance achieved with the naïve *BanKan* method. In fact, not only the ratio between *incomes* and *costs* is higher, but also higher are the *turnover* and the *service level*, and clearly smaller the *stockout ratio*. About this last measure, it is interesting to notice that it was reduced from 12%, on the KANBAN method, to 3%, when using the *BanKan*. A more attentive inspection of these results would lead us to conclude the naïve method reveals superior in almost every aspects.

We can now explain the reasons to choose the name *BanKan* for the naïve method. The first idea was to keep the "Japanese" phonetics as a tribute to the sense of simplicity and perfection with which the Japanese conquest our sympathy, as well as made possible the popularisation of technologies, mainly informatics and digital, which before seem to be given to the public only in small doses by monopolist enterprises. The second reason has to do with the fact that the *BanKan* is somehow the inverse of the KANBAN, once the stock "operator" is much more interested on dispatching the material from its stock than on the calculation of when and how much to order. The KANBAN was thought to make the stock available for a certain operation in a Production System, while the *BanKan* is thought to make the stock not available at all in the facility, while keeping the system running. Because of its Japanese phonetics the *BanKan* can also be a tribute to Taiichi Ohno, the father of JIT, and at the same time expresses the inverse reasoning of KANBAN and other standard methods of inventory control. In one sentence, the KANBAN controls, while the *BanKan* does not.

## 5. Comparing the KANBAN and the *BanKan*

To compare with more accuracy the performances of these two policies, the results from the simulation were later organized by facility and presented graphically. In figure 14, for example, it is represented the *average inventory* held at each facility during one year of operations, where from we can obviously conclude that it grows from the retailer to the factory while using the KANBAN, but stands constant and minimal when using the *BanKan*, as this method tends to set all the inventory in motion.

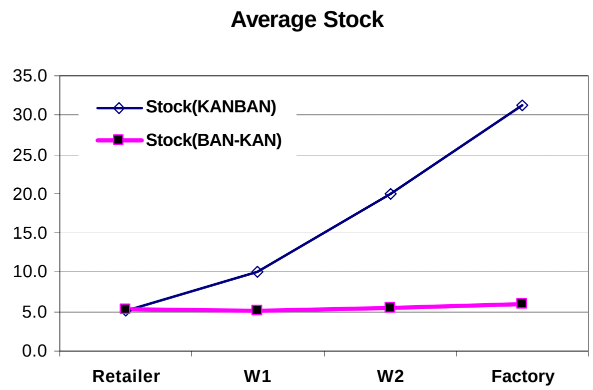


**Fig. 14** Comparing the *average inventory* along the Supply Chain

What concerns the *turnover* and the *service level*, both represented in the figure 15, the results show that the *BanKan* solution is obviously preferable at any level of the Supply Chain. With the KANBAN these measures show a tendency to decline as one approach the factory, while they are kept practically constant with the *BanKan*.

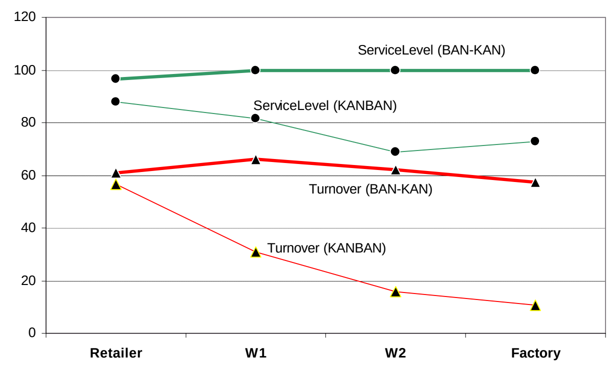


**Fig. 15** Comparing the *turnover* and the *service level*

The last comparison concerns the *costs* and the *incomes*, which are very important measures for realistic Supply Chains. And even in this case the results appear surprising. One could expect the *costs* to be higher with the naïve method due to the more frequent transportation of material, and that is what simulation have shown, anyhow, as it is represented in figure 16, the *ratio* between *incomes* and *total costs* continues higher in all facilities when using the naïve method. *Holding costs* were obviously also included and considered even with the inventory in motion.

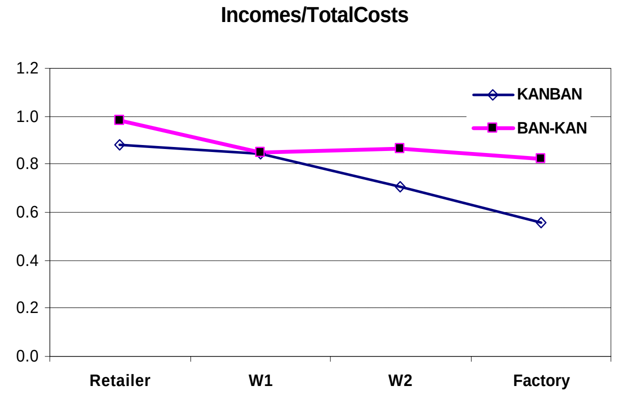


**Fig. 16** Comparing the *incomes/totalCosts*

There is, however, in this *naïve* process a negative aspect, which probably is the reason why managers do not use it in practice: the final cost of the product. As the figure 17 shows, the cost of the product rises when it approaches the retailer, as expected, and this implies an obvious increase on the price of the product at the last customer, once the transportation costs have been made to reflect in product price at each facility. In this particular case, in which was considered a null *business margin* in each facility (thus the price increase was only due to the transportation effect), it was observed a product cost at the retailer of about 60% higher that in the KANBAN case. So, at least this difference would have to be projected to the last customer.

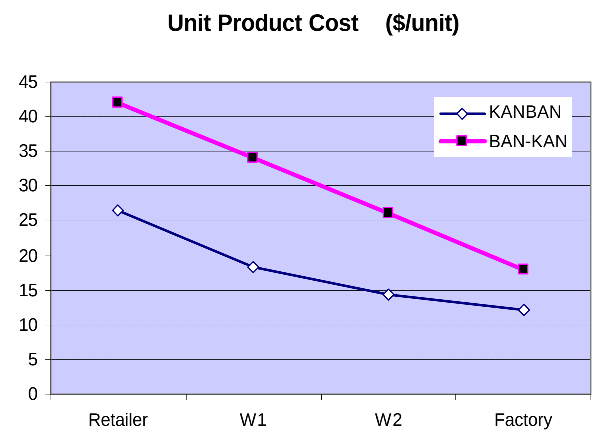


**Fig. 17** Comparing the unit product costs

It is also important to refer that the transport costs in this simulation were made dependent on the level of occupation on the delivering vehicle, as usually happens in real cases. It was, therefore, considered discounts of quantity. Anyhow, in all the facilities these discounts were the same. Such discounts are also responsible for the higher costs in the *BanKan* case, as the facilities order much less material quantity in each order than in the other case, turning the product prices higher.

## 6. CONCLUSIONS

The surprising results obtained by simulation on comparing these two reorder methods let us conclude that at least it could be interesting to study the effects of the naïve *BanKan* method in other kinds of Supply Chain, as well as under diverse demand patterns and with more than one product. At least, for the demand variability considered in the present case, the results have shown a superior operational performance while using the naïve *BanKan* method, where also it was observed much less *stockouts* at the retailer level than when using the KANBAN. This, for sure, must have a meaning, even apart from the fact this was an academic case study (Hewitt, 2001).

Another interesting conclusion coming out from this study is the fact that using the naïve *BanKan* method one does not have to care too much about speed in the delivery, but instead about its exactness. Actually, as the *BanKan* method is mainly regulated by time, and not quantity, this can take away from the managers and suppliers the constant stress of delivering faster and faster, and, instead of that, to let them plan their jobs with more precision and tranquillity in the time domain. If a supplier is able to delivery in two hours running as a crazy, for sure it will also be able to deliver in five hours spending less energy, running slower or, perhaps, serving more facilities than before. The only difference is that the quantity *Qo* will have to be a bit higher that in the previous situation. Extremely important is that the supplier will be at the client facility at the scheduled time in order that the synchronism with the demand at the retailer can be maintained high. Of course, this kind of behaviour would imply a sense of cooperation between all the Supply Chain operators, what again reveals the importance of *trust*.

Apart from this, using the *BanKan* at the “inner” facilities of the Supply Chain could probably also mean less space needed for inventory, less complex software for processing orders, less expensive stocking processes, which obviously would result in less expensive warehouses. Perhaps then the final price of the product could be enough reduced at the customer level.

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# Using Simulation to Analyse the Procurement of Additives for Lubricants in the Oil Refinery of Porto, Portugal

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**ABSTRACT**

Data in this article results from a study of simulation about the procurement of additives for lubricants in the Oil Refinery of Porto (Portugal). Here we describe the real case under study as well as the method we have chosen to board it by means of simulation, which finally leaded us to some interesting results regarding the choices on purchasing the additives from the suppliers. Costs including transportation, holding and stockouts have been considered during the simulation as well as in the final conclusions, which let us recommend a more frequent reordering of materials at the lubricants plant. This we expect to result in the saving of around 0.3M€/year in global costs.

## 1. Introduction

This Oil Refinery (Fig. 1) is located in Leça da Palmeira, an important suburb of Porto, and is operating since 1970. Even if it already had been used with a processing capacity of 7.5 MTon of crude per year in 1975, since 1982 its capacity has been maintained in the 4.4 MTon/year, mainly due to the installation of a second refinery in the south of the country (GalpEnergia, 2003).

**Fig. 1** View of the Refinery of Porto, Portugal

However, since its beginning the refinery included a Lubricants-Base Plant, which at the present has a producing capacity of 150 KTon/year, and where diverse kind of lubricants are produced to the industry and to the general market. The present study concerns with the procurement related with this plant, which is only a part of the refinery.

The study has been conducted with the kind participation of engineer Mr. José Carlos Fernandes, from *GalpEnergia*, the company responsible for the refinery, who at the time was in charge of the *Department of Logistics and Stock Management of Lubricants*. The main objective was to study in more detail the process of purchasing near 200 different additives for lubricant production, ordered from 10 different European suppliers, and with different transportation costs based on the quantity ordered. Notice that final lubricants normally include around 10% of additives. The Supply Chain in study was then a procurement network whose final node was this plant, as figure 2 illustrates, with the suppliers spreading from England to Spain.

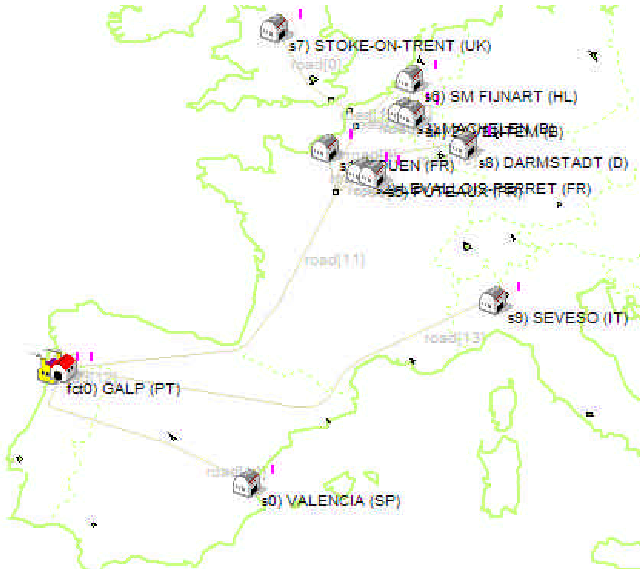


**Fig. 2** The Supply Chain in study, with 10 European suppliers

The price due to the transport of one unit of product from each supplier to the plant was dependent on the supplier and on the quantity ordered, so, the primary intention was to seek for the quantity to order that would minimize theses costs at the plant's level. However, later we have opted to consider instead the costs of transportation, products, product holding and product stockouts, since total costs were considered a better financial measure to support practical decisions.

The case was also useful to help on the validation of a Supply Chain Simulator described in a previous article (Feliz-Teixeira & Brito, 2003), as well as to let us conclude about the methodology being used and about the sort of problems to face while modelling a real system of this kind.

## 2. The process of building the model

The first important aspect to have in mind when preparing to simulate a real system is to dominate the process of building the model, beginning by the simulation tool. The tool used here was developed in C++ during the Ph.D. studies of Feliz-Teixeira and it was specifically oriented to Supply Chain Simulation, being therefore prepared to represent in a very easy way the elements of this kind of systems. With this tool, to build the model could be reduced to the following 5 procedures:

(1) <u>The representation of the facilities in the "theatre of operations"</u>: the facilities have been located in the simulation window without any special geographic precision, as that aspect was irrelevant to the present study. Anyhow, each facility was placed carefully enough to maintain a relative fidelity to its real location, with the help of a map previously drawn in the simulator window (see figure 2). To help on this, *GalpEnergia* has made available a document with the post addresses of the suppliers.

(2) <u>The definition of the transport paths connecting the facilities</u>: these paths have also been traced without great precision in the simulator window, as in this particular case the transport costs were already defined at each supplier by a list of prices per unit transported. In those transport costs the factor distance was already included. Anyhow, the transport paths traced on the simulator try to follow the most probable lines of delivery used by the suppliers, and serve to give an idea of the delivering times as well as to introduce extra variability on the supplier's lead-times. *GalpEnergia* has made available a document with the expected lead-time for each supplier.

(3) <u>The definition and characterization of the products available to the system</u>: this important step let us insert into the simulator, using a dialog like the one of figure 3, the first relevant information about the 195 different additives with which the plant usually works. Notice that, as it was considered the *product unit* (SKU) for all the products the standard barrel of 200 Kg, the maximum number of SKUs per truck (of 24000Kg) was assumed to be 120.

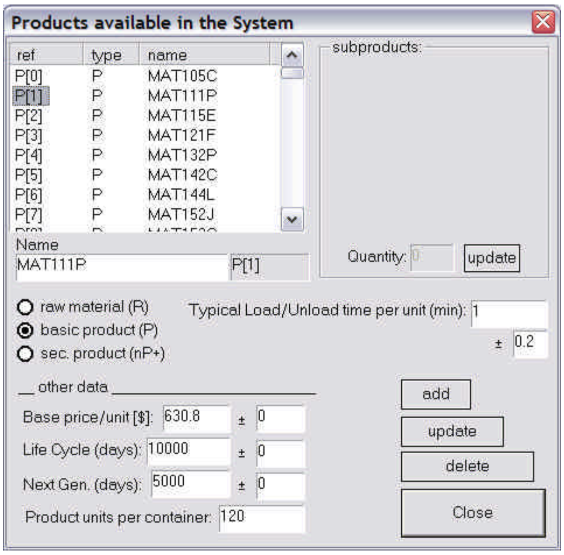


**Fig. 3** Dialog Box to insert the products into the simulator

In each product one also included its reference-name and its base price (at the supplier's level), and this list was several times carefully inspected to ensure no mistakes were inserted in the simulation from the base. This data was primarily provided by *GalpEnergia* in the form of an EXCEL document, and directly retrieved from the plant's data base.

(4) <u>The configuration of each facility, including the transport policy and the material's reorder model</u>: once the system was geographically "represented" on the simulator and the available products inserted, the general configuration of each facility had to be established, including the definition of its transport cost policy and the material's reorder model.

In the first case, the suppliers have been configured to use *cost echelons of transport*, which were provided by *GalpEnergia* in the form of costs per Kg based on different ranges of weight, which then have been transformed to express the costs referred to the percentage of occupation on a truck of 24000Kg, considering each SKU a barrel of 200Kg. This data was assigned to the correspondent facility by means of a 5 echelon attribute filled in by the dialog shown in figure 4. The final transport cost of a certain order could therefore be automatically computed as long as its percentage of occupation in the truck was known. More than 100% occupation was made to incur in 10% extra costs, as many real suppliers establish.

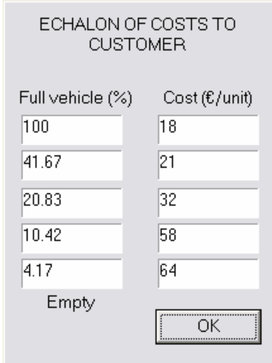


**Fig. 4** Dialog Box to define the transport cost echelons

On the other hand, the definition of the material's reorder model and other information related with this aspect was inserted at each facility by means of a dialog like the one shown in figure 5. Each product was chosen to use the reorder model (r, Q), and then it was defined the amount of *safety-stock* and the *quantity to order*, as well as the *setup-cost*, the *Time for Full Satisfaction (TSF)*[1] and, finally, the *supplier*. This was done manually to the 195 products in the list, even if only 108 could be linked to a valid supplier and finally simulated. The suppliers were considered being supplied by perfect instantaneous delivering suppliers.

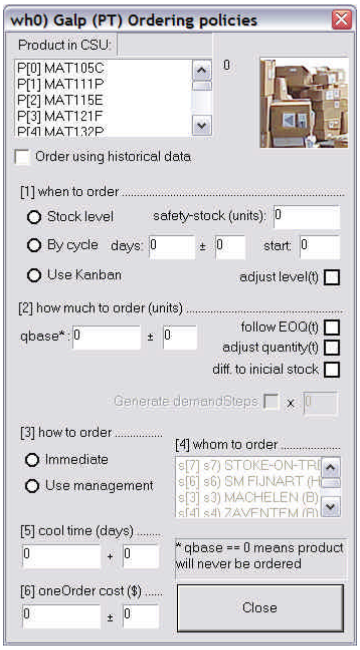


**Fig. 5** Reordering Policy configuration

All the facilities were made to operate with an 11.5%/year *bank lending rate*, and null business *margin*, meaning that the purchase cost was only affected by the basic product cost and transport cost.

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[1] This simulator uses this measure to retrieve a quantitative idea of clients "satisfaction", applying it not only to last customers but also to any facility in the supply chain. Once established the *Time for Full Satisfaction (TFS)*, any order arriving from the supplier within this delay will be considered 100% satisfaction, otherwise the satisfaction decreases proportionally to the extra time spent...

(5) The characterization of the demand at the plant: the demand information was obtained from documents of the real plant consume during the year of 2003. This data was a monthly historical record. Then, based on such data, two main approaches have been chosen to simulate the case:

1) *Inserting directly the historical demand into the simulator.*
2) *Using a* Normal *statistical approach of this historical data as the demand to insert in the simulator.*

Obviously, in the first case the demand had to be considered monthly, as it is in reality, but, in the second case, by means of the statistical approach, we also could "hint" the consume as if it would be sampled two in two weeks or even weekly. This let us compare results using different frequencies to sample the real demand. However, before inserting this information into the simulator it was needed to transform the 195 lines of original historical data, which were in Kg, into a monthly consume of barrels of 200Kg. Of course, this implied a rearrangement on de monthly demand pattern, as the old demand had to be integrated in time till reaching the amount of a new barrel. This work has been done with the help of a little C program developed to compute such demand transformations for all the 195 independent lines of historical data. Finally, as a result from this approach, we could create the following 4 basic scenarios to be simulated: *hist(30)*, which was driven by the original monthly demand, *stat(30)*, driven by the *Normal* statistic version of the monthly demand, *stat(15)*, considering the statistical demand sampled fortnightly, and *stat(7)* representing the statistical demand sampled weekly. These basic scenarios could later be compared by simulation, each one tested under the 5 different *transport cost echelons* previously considered.

## 3. Model validation and corrective factors

The simulation process has been planned to help us on reaching two main objectives: first, the confirmation of the validity of the results obtained with the simulator, at least for the present case; and, second, the studying of different approaches to purchase the products, considering the 5 different *transport cost echelons* with which the suppliers operated. This section relates with the first process, that is, the model validation.

The process of validation was restricted to the fact we only had access to documents about the monthly *plant's consume*, *average cost of each product* and *actual inventory level* at the plant's warehouse. From these values we could calculate the *average plant consume* as well as the *accumulated plant consume*, the *accumulated costs of products* and the *average inventory level at the plant's warehouse*, regarding the activity on the year of 2003. These were the 4 realistic parameters with which we later could compare the simulation output in order to validate the model. The following "real" data have been retrieved from documentation based on the 108 products that definitely could be simulated (the others had no assigned a valid supplier inside the network in study):

- Average[2] inventory in 2003 (barrels) = 2484.8
- Average plant consume in 2003 (barrels) = 477.7
- Accumulated plant consume in 2003 (barrels) = 5731.8
- Accumulated costs of products in 2003 (K€) = 2835.3

With the intention to compare this data (*Rj*) with the simulator output data (*Sj*), each of the 4 basic scenarios previously referred was made to run for one year of simulated operations, considering null the transport costs. In each case the results were obtained in the form represented in the next two figures (Figs. 6 and 7), where from data could then be obtained to fill table 1. Notice that the *accumulated cost of products* was considered the *purchasing costs* plus the *stockout costs* (as the unit stockout cost was simply made equivalent to the product cost in this model).

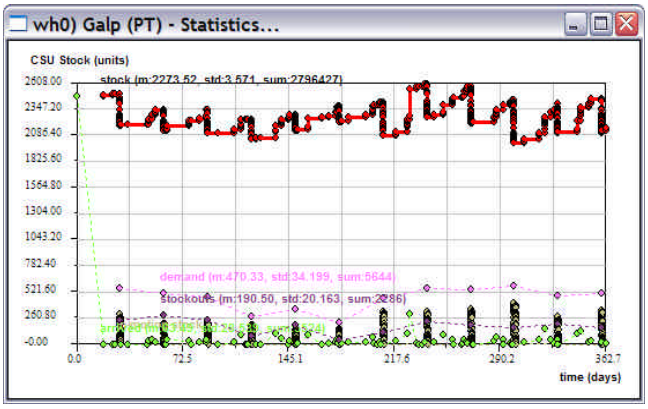


**Fig. 6** First view on the inventory level and demand achieved by simulating the scenario *hist(30)* for one year of operations

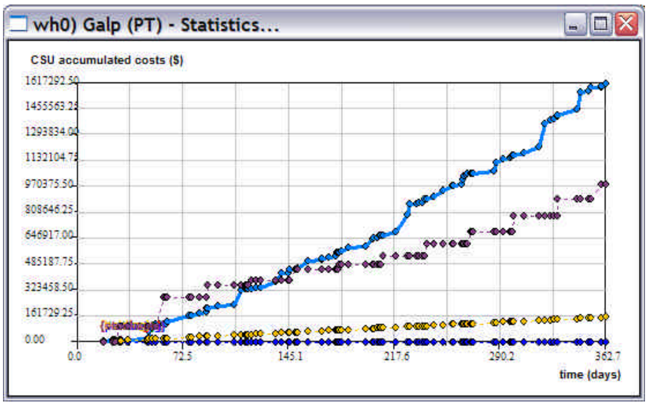


**Fig. 7** Accumulated costs obtained by simulating the scenario *hist(30)*, where purchase, stockout and holding costs are represented

| | *hist(30)* | *stat(30)* | *stat(15)* | *stat(7)* |
|---|---|---|---|---|
| avrg inventory level (barrel) | 2273.5 | 2069.9 | 2067.1 | 2096.1 |
| avrg consume (barrel) | 470.3 | 495.2 | 184.8 | 70.1 |
| acc consume (barrel) | 5644 | 6437 | 5358 | 4607 |
| acc costs of products (K€) | 2771.1 | 2984.9 | 2491.6 | 2089.8 |

**Table 1** First results achieved by simulation, for comparing with real data

From the data of this table (*Sj*) and the real data (*Rj*) another table was built (table 2) in which the percent deviations in relation to the real values could be estimated, applying the formula:

$$dev\% = 100\,(Rj - Sj)/Rj \qquad (1)$$

[2] Not really averaged, but instead estimated as the stock level in June 2004

| | *hist(30)* | *stat(30)* | *stat(15)* | *stat(7)* |
|---|---|---|---|---|
| avrg[3] inventory level (%) | -8.5 | -16.7 | -16.8 | -15.6 |
| avrg consume (%) | -1.5 | 3.7 | -61.3* | -85.3* |
| acc consume (%) | **-1.5** | **12.3** | **-6.5** | **-19.6** |
| acc costs of products (%) | **-2.3** | **5.3** | **-12.1** | **-26.3** |

**Table 2** Estimated deviations between simulated data and real data

Based on these results we could already make some idea on what to expect from future deviations in each scenario. Actually, from this we could conclude to expect a deviation from the real values of less than 3% in the *hist(30)* scenario (what can already provide a validation for the model), as well as expect that the *stat(30)* scenario will inflate the results, while the *stat(15)* and *stat(7)* will deflate them. Consequently, a corrective factor must be applied to each of these scenarios in order that in the end their results can be compared in terms of the same scale of measures. Thinking on *Kj* as the factor by which each parameter must be multiplied to approach its "real" value, we simply have decided to calculate it from the expression:

$$Kj = \text{Average}(\, Rj/Sj \,) \qquad (2)$$

Where the *Average()* function was applied only to the accumulated values, since they are considered to be more reliable for validation than simple values, as they act like the *summation of control* used in spreadsheets. By means of such calculations, the following corrective factors have been found:

| hist(30) | stat(30) | stat(15) | stat(7) |
|---|---|---|---|
| $K_1$ | $K_2$ | $K_3$ | $K_4$ |
| **1.02** | **0.92** | **1.10** | **1.30** |

**Table 3** Corrective factors for the different scenarios

Which later have been applied to the preliminary results.

## 4. The simulation's strategy

As the main objective of this study was to find the best purchasing approach based on the *transport echelons* established by suppliers, each scenario have been simulated according to seven different product occupation levels in a truck of 24000Kg. Each level was indirectly establishing the *minimal order quantity* to purchase to the supplier in each particular *order*, as each product quantity on that *order* was increased with steps of 1 unit (SKU) till the entire *order* reached the level's "mark". Notice that the same order can contain several products. Thus, these occupation levels were in fact forcing the *minimal truck occupation* to a certain predefined value. Anyhow, in the same simulation the predefined level was maintained the same for all the suppliers in the network, and not different levels to different suppliers were considered. The following truck occupation levels were tested in the study:

*MinOccupLevel = 0%, 4%, 8%, 16%, 32%, 64%* and *100%.*

Once the 0% level was chosen, the scenario was made to run during 365 days of simulated operations, along five replications, before data was collected. Then, the new level was chosen and the same process was repeated till the last level (full truck) was simulated. This was done for each of the scenarios in study. Results like those shown in figure 8 were obtained with the simulation of each scenario.

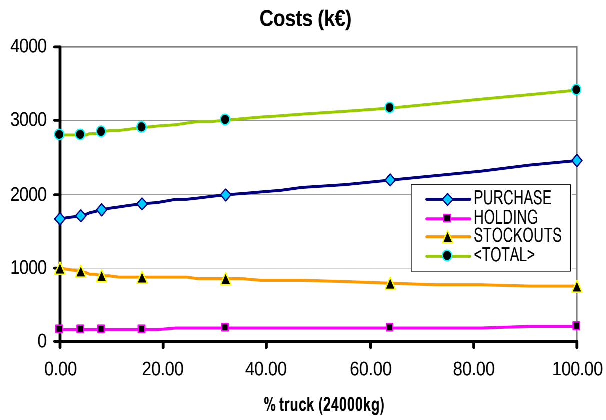


**Fig. 8** Variation of costs with different truck minimal occupation levels, obtained by simulating the scenario *hist(30)*

From this graph, the best occupation level was chosen as the one which minimized the total costs, which in this case corresponds to 0%, meaning the best option is to purchase exactly what the inventory model requests without worrying about any transportation effects.

Along with these results, also the *average inventory* level was calculated and plotted graphically, as the example of figure 9 shows for the case of scenario *hist(30)*.

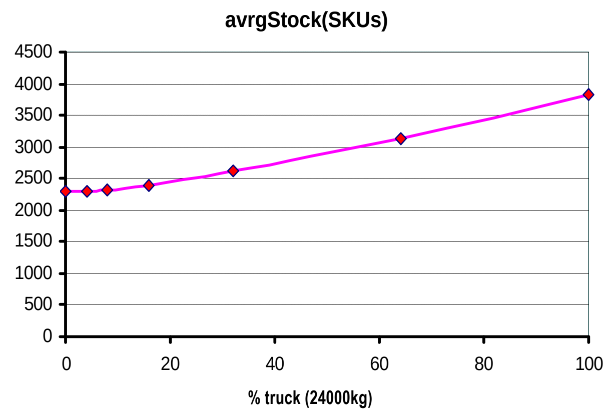


**Fig. 9** Variation of average inventory level at the plant's warehouse with different truck minimal occupation levels, obtained with scenario *hist(30)*

And, finally, also the average values and variations observed during simulation on the plant's warehouse performance were computed, in terms of some standard logistic metrics (fig. 10), in this case mainly focused on the *variable costs*, *turnover*[4], *service*

[3] Only used as a qualitative measure
* Notice that increasing the demand sampling rate implies a decreasing on the average demand. These values have no special interest for the model validation.

[4] The *turnover* was computed here like in a single product inventory, thus there will be a quite difference from the value one expects from practice

*level* and *stockout ratio*. This way one could record the behaviour of each measure along the entire spectre of purchasing policies. For example, from this panel one can expect to observe, along these seven different policies, an average value for *service level* of 66.2% with a variation extending from 50.8% to 76.8%.

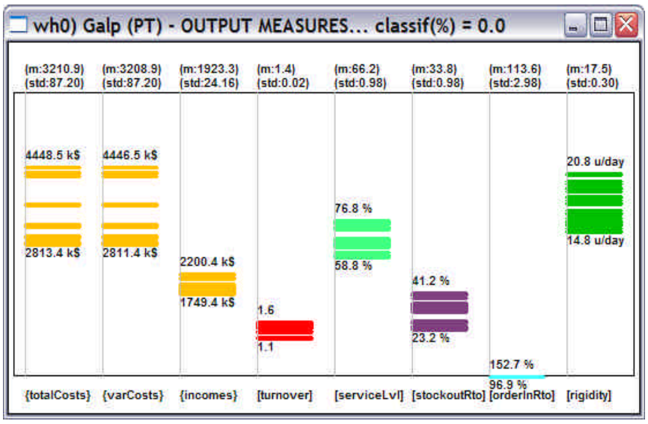


**Fig. 10** Plant's warehouse performance obtained with scenario *hist(30)* along the entire spectre of purchasing policies (total runs = 30)

The *best results* obtained with each scenario were then chosen, and this data organized per scenario and joined together in a new table. Finally, the respective corrective factors (*Kj*) were applied to this table and the *final results* obtained, which will be presented in the next section.

Before passing to the next section, however, it is important to make noticed that also the following conditions were considered in the models:

- *BusinessMargin* = 0 at all the facilities, meaning the costs of the products were precisely the same as provided by *GalpEnergia*.
- *No Backorders.*
- *PurchasingCosts* = *ProductCosts* + *TransportCosts.*
- *BankLendingRate* = 11.5 %/year.
- Transportation always available at the suppliers, no need to wait for the arrival of a truck.
- *OrderSetupCosts* = 0, because they were in practice almost null in comparison with the products costs.
- *TimeForFullSatisfaction (TFS)* at the plant was considered 3 ± 0.5 days (indirectly rules the *stockout ratio*)
- *TimeForFullSatisfaction (TFS)* at the plant's warehouse was considered 30 ± 3 days.
- Reorder model *(r=ro, q = Q(t))*, with *ro* the actual safety stock and *Q(t)* to follow the maximum between *average demand* and the *accumulated demand between supplies*.

## 5. Final results and comments

The four basic scenarios were operating with the inventory model *(r=ro, Q(t))*, as previously referred. Anyhow, to let us test this model with other values, after each of these scenarios has been simulated the *average demand* during the 365 days of operations was computed, as well as the *accumulated demand between supplies*. Then, the original scenario was copied into a new scenario on which a change would be made in the inventory model: *ro* was replaced by this *average demand* and *Q* was substituted by the *accumulated demand between supplies*. Then, the scenario was also simulated. For this reason, the final simulated scenarios became the following eight:

1) *hist(30)* – original historical data, model (r=ro, Q(t)).
2) *hist(30)_ss_qq* – historical data, model (r=avrgDem, Q=accDemSuppl)
3) *stat(30)* – statistical data, model (r=ro, Q(t)).
4) *stat(30)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)
5) *stat(15)* – statistical data, model (r=ro, Q(t)).
6) *stat(15)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)
7) *stat(7)* – statistical data, model (r=ro, Q(t)).
8) *stat(7)_ss_qq* – statistical data, model (r=avrgDem, Q=accDemSuppl)

And the graph presented in figure 11 shows the results before correction obtained precisely with these scenarios, numbered from 1 to 8, considering their *best occupation level*.

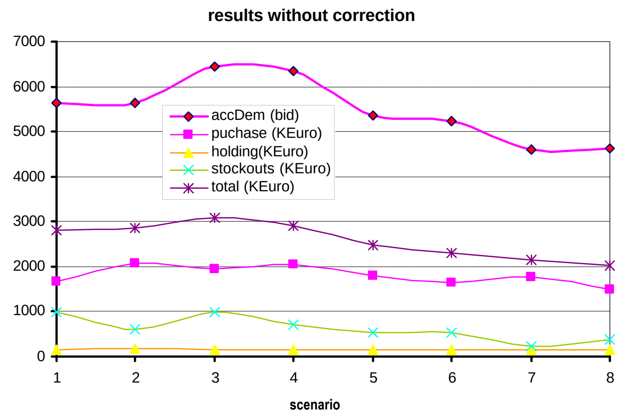


**Fig. 11** Results before applying the corrective factors

From this figure the behaviour predicted earlier is now evident. As expected, *stat(30)* scenario inflates the results, while *stat(15)* and *stat(7)* scenarios deflate them. Much of this is a consequence from the slightly differences at the demand generated pattern that accumulate along the 365 days of operations, as also can be noticed from the figure. The upper line represents, in fact, this *accumulated demand*, which ideally should be a horizontal line. It is thus obvious that no conclusions could be retrieved from this data before applying the corrective factors. Doing so, we finally obtain the following costs figure:

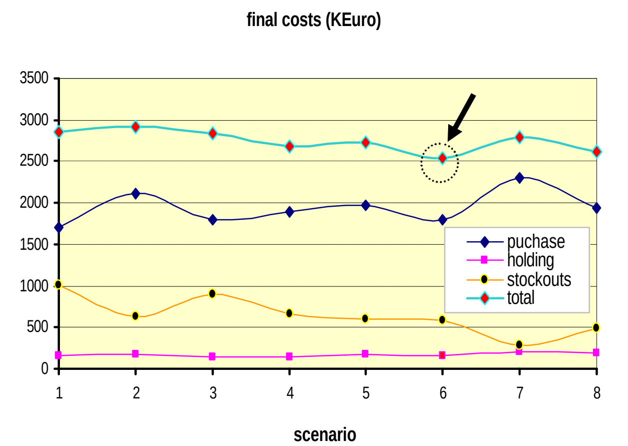


**Fig. 12** Final results, concerning accumulated cost during a year

Notice that if this correction would not be applied we could have been induced in mistake by choosing the *stat(7)* scenario as the most interesting option on the preliminary results. In fact, the most interesting is scenario 6, known as *stat(15)_ss_qq*, since it obviously leaded to the minimal total costs accumulated along the year. Compared with the actual situation, this would mean a save of around 300 K€, measured by the figure. As it was also observed that the <u>best truck occupation level</u> for this scenario was 8%, one can finally conclude:

*"The best approach to operate the plant's warehouse would be to ensure a <u>fortnightly inspection</u> of its inventory and, once operating with the inventory model (ro, Qo), to set <u>ro</u> as the <u>average demand</u> (at each product) and <u>Qo</u> the respective expected <u>accumulated demand between supplies</u>, not forgetting to order always at least <u>8% of a truck</u>. The total expected saves would be around <u>300 K€</u> in one year of operation".*

IMPORTANT REMARK: One must not forget that these results have been obtained considering only 108 of the 195 products previously inserted in the simulator, which would represented a more realistic view on the plant's demand.

## 6. CONCLUSIONS

Any conclusions must count with this last remark. Only those products which could be linked to the list of suppliers considered in these models have been simulated. Consequently, the results presented here will obviously express this fact, meaning that the conditions of their validity do not reflect the overall plant's demand and, probably, they will not fit perfectly with those obtained in practice. Anyhow, they seem consistent and quite interesting, as they confirm important values previously calculated from real data, and seem to point to a higher frequency on inventory revision with the objective of reducing total costs, a trend of nowadays on trying to minimize forecast inaccuracies. Actually, it is in general more difficult to forecast for a long period of time that for a shorter one, at least when the demand is "well behaved" like in the present case.

What concerns the original objective of analyzing the costs variations with the different *echelons of transport*, it was observed that in all the scenarios except the *stat(15)_ss_qq* the best approach was the 0% *minimal truck occupation*, meaning it was to purchase exactly what the inventory model would request without worrying with any transportation effects. For that reason this problem was naturally absorbed by the problem of sampling the demand with different rates, which during the simulation was getting more relevancy than the former issue. This was due to the fact that in most of the cases the original truck occupation was already naturally high, as figure 13 shows for the case of *hist(30)* scenario, with an average value between 30 and 60 %. Lower levels of occupation were thus automatically "ignored" by the simulation, turning this issue less relevant.

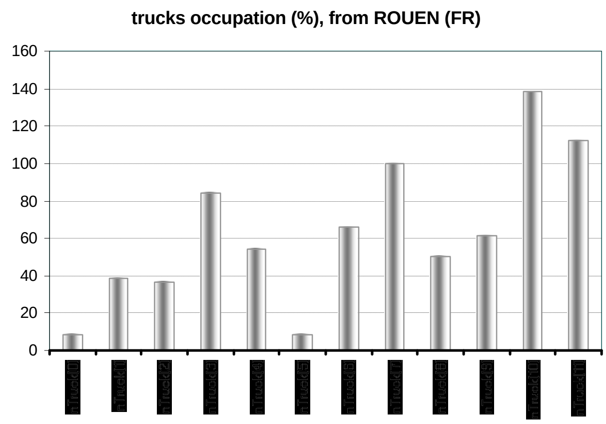


**Fig. 13** Original truck occupation in the *hist(30)* scenario

In respect to the methodology, it appeared to be firm and good, and leading to an interesting way not only of validating the model but also of making possible the comparison of different scenarios by means of applying some *corrective factors*. Also the verification of certain aspects of the simulator could be done, because with this study some "bugs" were detected in its software and later repaired, mainly in the procedures for computing the *holding* and the *purchasing* costs.

The most important issue, however, in what concerns a more serious study of this plant, is related with the fact that not all the important products on the real demand could be simulated and that for sure implied a deviation on the results from real data. As shown in figure 14, it was observed that some of the products were extremely expensive and other relatively cheep, but not all of those expensive ones could be simulated in this study. From this figure one can also get an idea of the probable deviation that could have been committed in this approach because of this problem.

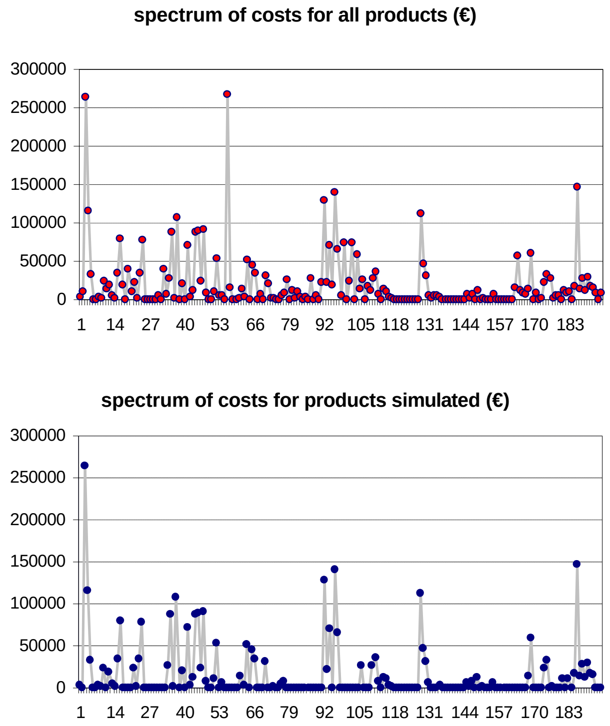


**Fig. 14** Comparison of costs involving all the 195 products in the plant and the 108 simulated products

It seems obvious that for future studies first we will have to ensure that the most economical significant products will be represented and turned able to be simulated. In order to improve the simulation of this interesting case, we would in the future need to focus the attention in the following main aspects:

- Ensure the simulation of all A type and B type products.
- Improve the statistical demand generator, maybe.
- Count with more costs: stocking, order setup, etc.

We hope that a more accurate study on this case can be completed in the future, perhaps following the careful analysis of these results that at the present is being made at *GalpEnergia*,

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# On Measuring the Supply Chain Flexibility

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## ABSTRACT

This paper presents some lines of thinking related with the establishment of a concrete mathematical basis to measure the ability of enterprises in a supply chain to maintain equilibrium under unexpected variations. It will be argued that *flexibility* will be the most appropriate term to classify the concept behind such idea and that *agility* can be understood as a special case of *flexibility*. Then, a simple theory of *flexibility* directed to demand variations in the supply chain is deduced and commented, as well as some results achieved by dynamic supply chain simulation presented and discussed.

## 1. Introduction

*Flexibility* and *agility* are two expressions already well established on the field of Business, even if neither of them had been quantified in the form of a metric that could be applied without misleading by any manager in any part of the world. There is still a diffused and cloudy idea about what in fact each of those terms mean regarding business and management, due to the fact they are multi-variable concepts and normally used to express the same ideas in day-by-day language. Apparently, the handling of such designations depends on the school of thinking as well as on the area of work it is related to. For instance, *flexibility* is more used in manufacturing, where it means something like the ability to answer fast and reliable to needs of changing in the product mixing, while *agility* is most of the times associated with supply chain and thought to be something like the ability of fast response to changes in the overall enterprise (Goldman et al., 1995). Probably, one also can recognise in the usage of such terms a certain pattern of the kind which let Wendy Currie[*] (2000) say "*the historical analysis of these change management panaceas shows that eventually their popularity and applicability declines and they are replaced by new panaceas which, although labelled differently, are in many ways similar to the predecessors*" [1], while referring to concepts like TQM, JIT, BPR and PI. The fact is that it continues to be extremely difficult to find a single and wide accepted definition for *flexibility* and for *agility*, and even more difficult to find their metrics.

For that reason we decided to start not using such words. Instead we will start using the concept of *elasticity*, which is already deeply treated on Physics by the *Theory of Elasticity*, thus meaning it will be understood by all the scientific community.

Then, the supply chain will be considered a mathematical system with the form of a network with nodes and arcs where materials and information flow. In such a system, each node will exhibit a certain ability to return to its equilibrium concerning the flow traversing it (we will only consider the flow of materials), with such flow being highly dependent on the material sink and source policies governing each node. Obviously, the complexity of the problem will exponentially increase with the increase of the number of nodes in the chain and their own complexity. Based on those aspects will try to establish a practical measure of *flexibility*.

In this paper we first make some comments regarding nomenclature and then we will derive the theoretical basis behind our perspective of measuring *flexibility*. This has naturally resulted from the need of trying to quantify *flexibility* while developing a Dynamic Supply Chain Simulator (Feliz, Brito, 2003)[2] capable of using such metrics. Finally, we present some practical results obtained by simulating a didactic supply chain case.

## 2. Some Theoretical considerations

Although the *Theory of Elasticity* is somehow a field of knowledge demanding the manipulation of advanced mathematics, mainly differential equations, the approach we present here will be less complex than that and somehow a mixture between signal processing and elasticity. Our expectation is that this will turn these ideas wider applicable in practice and will lead to a simple method of measuring the ability of a system to change state while maintaining the equilibrium.

The theoretical basis of elasticity comes from the problem known in literature as the *Simple Harmonic Oscillator*, which since long time ago is completely described in Physics literature. An excellent and clear description can be found in the book from Murray R. Spiegel, "*Schaum's Outline of Theory and Problems of Theoretical Mechanics with an Introduction to Lagrange's Equations and Hamiltonian Theory*", McGraw-Hill, 1967.

From reading its 4th chapter one can realize that the *elastic forces* are in fact forces directed to the state of equilibrium, but also recognize that those forces are more related with the ability to oscillate around such a state than with the ability of returning to it. *Elasticity*, as a quality derived from the *elastic constants* of the materials, must then be understood as an ability to oscillate and not precisely as an ability to return to the equilibrium. Figure 1 represents a simple system oscillating around an equilibrium state (*Qo*) with a certain period (*To*) of oscillation, period that is dependent on the *elastic constant*. The higher the value of this constant (or the *elasticity*) the higher the rate of oscillation and

[*] Professor and Director of the Center for Strategic Information Systems at Brunel University, UK

thus the lower the period *To*.

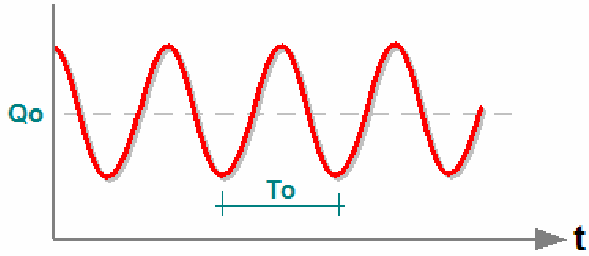


**Fig. 1** A pure elastic behaviour

But this of course does not serve our intents, and then we simply refuse to use the term *elasticity* to express the idea of maintaining the equilibrium when a change of state in the supply chain occurs.

However, if we now introduce a certain *force of dumping* in the *Simple Harmonic Oscillator*, such a system will in fact start to exhibit a tendency to return to its state of equilibrium, thus behaving much more similar to the effects we are interested to measure concerning the supply chain responsivity. In figure 2 it is shown the three different modes how this new system can approach the new state. They are known in literature as the *over-dumped* mode, the *critical-dumped* mode, and *under-dumped* mode.

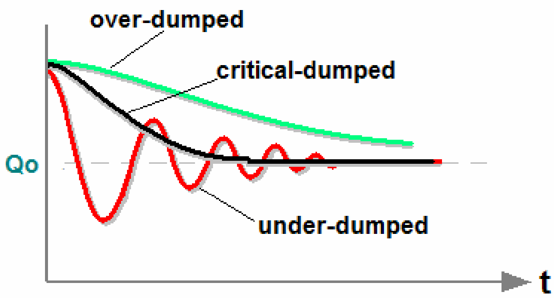


**Fig. 2** A dumped elastic behaviour

Once in the *over-dumped* mode the system naturally returns to *Qo* after the initial perturbation is removed, but this time is longer than the optimal response time and thus it will turn the system low. On the other extreme, when *under-dumped*, it will approach *Qo* swinging and thus exhibiting great instability. Anyhow, once *critical-dumped*, the system not only will reach the equilibrium faster but also spending the minimal energy. Systems in such conditions are said to be *well-dumped* or *tuned* to their characteristic frequency of oscillation $fo = 1/To$.

In our point of view, this dumped behaviour already satisfies a certain idea of *flexibility*, for it shows how the system will return to the equilibrium after an instantaneous perturbation. Therefore we are tempted to conclude that a system will be more *flexible* when its *Time to Return to Equilibrium (Tq)* is reduced. At the same time, we conclude that a measure of such a time interval would in fact give us an idea of the *flexibility*.

Another result of this approach is that *agility* could be interpreted as a specific behaviour of *flexibility*, as it points towards the elegancy of movements and thus to the ability of achieving the goals with less energy spending. Thus, *agility* would be understood as the *critical-dumped* condition of *flexibility*. These would lead us to the following statements:

*The system is agile when it faster recovers the equilibrium without going into oscillations, implying the minimal energy consumption.*

or, saying in another way:

*The system is agile when operating in a regime or well-dumped flexibility.*

## 3. The metrics for *flexibility*

In the previous section we have suggested that *flexibility* would be inversely proportional to the *Time to Return to Equilibrium (Tq)*, thus, a simple way to express the *flexibility* is inverting the things and consider:

$$FLEXIBILITY \sim 1 / Tq \qquad (1)$$

This expression is equivalent to the *Rate of Returning to Equilibrium*, or, in other words, to the *Ability to Absorb Chocks*.

This is of course a general definition for *flexibility*, and so it must hold for any systems as a basic concept, not only for supply chains. Anyhow, the challenge now is to find a way by which *flexibility* can be measured in practice. For that purpose we will use a simple representation of a state of equilibrium along the time. In fact, if we believe *flexibility* to represent the ability of the system to maintain its equilibrium, then a way to turn "visible" such ability can be plotting over time or the state itself or the function that represents the equilibrium of that state.

With such intents, let us focus the attention on just a node of the supply chain and on the state of its inventory. Obviously, the node will be in equilibrium (in terms of materials flow) when the rates of input and output of materials will be the same. That is, when:

$$R_{out} = R_{in} \qquad (2)$$

Being $R$ a quantity of materials per unit of time, a way of calculating these quantities in practice will be to consider the amounts of materials ($Q_{in}$) entering the node during the time interval ($dT_{in}$) of two consecutive arrivals from the supplier, and the amount o materials ($Q_{out}$) leaving the node during the time interval ($dT_{out}$) between consecutive services to the clients. Equation (2) can then be written as:

$$(Q_{out} / dT_{out}) = (Q_{in} / dT_{in}) \qquad (3)$$

or, arranged in another way:

$$(Q_{out} / Q_{in}) \text{ x } (dT_{in} / dT_{out}) = 1 = EQUILIBRIUM \qquad (4)$$

Anyhow, if we look at the node only at the moments the material arrives from the supplier ($dT_{out} = dT_{in}$), we can say the node will be at perfect equilibrium when the quantity of materials going out equals the quantity of material coming in. In any other circumstances, the node will be out of equilibrium.

Thus, a simple and practical form to represent this equilibrium function is to compute it every time the material arrives, and this will be achieved by counting $Q_{in}$ and $Q_{out}$ during each time interval $dT_{in}$ followed by an operation of division.

It is also important to notice that with this method the function EQUILIBRIUM(t) will be a discrete function "sampled" by the frequency of arrival, as shown in figure 3 (such frequency is given by $f_{in} = 1 / dT_{in}$, as it also can be deduced from the same figure). This important aspect shows that the node is not "during all the time connected" to its suppliers, and for that reason it will face "certain" difficulties on following "certain" demand changes, resulting obvious that systems with longer $dT_{in}$ will have more difficulties to recover from demand “chocks”. We let to the Supply Chain Managers the investigation on how to reduce $dT_{in}$.

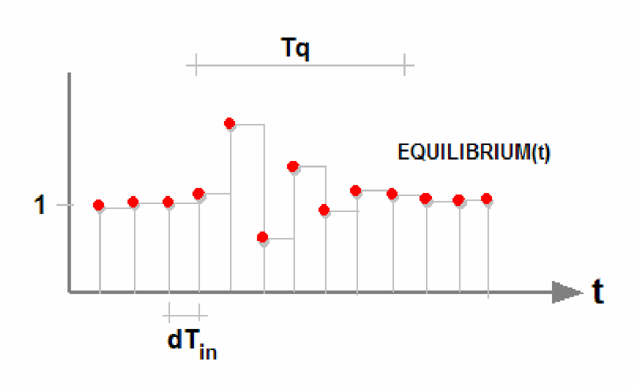


**Fig. 3** A perturbation in the EQUILIBRIUM(t) function

At the moment, and if for simplicity we consider the frequency of arrival to be fixed, the important is to realise that any measure of the *Time to Return to Equilibrium* (*Tq*) by means of this equilibrium function will lead to values multiples of $dT_{in}$, that is:

$$Tq = n\, dT_{in} \tag{5}$$

Where $n$ is an integer assuming values 0, 1, 2, 3, etc., representing the number of arrivals from the supplier. Finally, comparing equation (5) with equation (1) we will deduce:

$$FLEXIBILITY \sim (1/n)\,(1/dT_{in}) = (1/n)\, f_{in} \tag{6}$$

That is, the *flexibility* will be directly proportional to the frequency the material is arriving from the supplier ($f_{in}$), as well as inversely proportional to the number of such arrivals ($n$).

And this is an interesting result, first because it comes close to a range for this metric, saying the *flexibility* belongs to the interval $[0, f_{in}]$ with an exception of $\infty$ when the perturbation does not affect at all the equilibrium ($n = 0$), and also because it is in accordance with the “empiric” principle of reducing the reorder quantity in warehouses and the lot quantity in manufacturing systems. Actually, these results fit perfect with the common idea that *a system will get more flexible as its frequency of replacing material rises*. It also results from these considerations that to achieve the optimal *flexibility* (or the state of *agility*) in practice one must adjust (by trials?) $f_{in}$ and the reorder quantities in order to minimize *Tq* without letting the system entering in oscillation. In principle, we believe this can be achieved using the scheme suggested in figure 4 with steps of demand to induce perturbations in the system, by means of simulation.

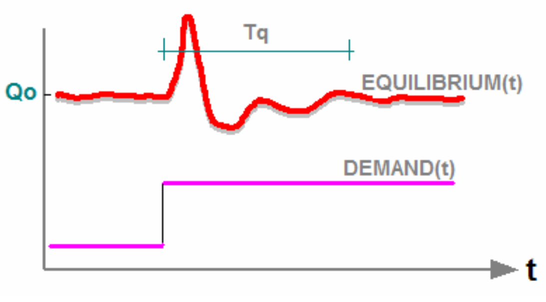


**Fig. 4** Using demand steps to measure *flexibility*

Although this seems a reasonable proposal to measure the *flexibility*, it is important to recognize it comes out from a one dimensional analysis of the problem. In fact, it just considers the variable *time* ($t$) and completely ignores the variable *material quantity* ($Q(t)$), and this would mean a system would be the same *flexible* whether going to equilibrium by moving lots of material or by moving only little quantities of it. Of course, it seems reasonable to consider the second case would be more *flexible*, despite the same *Tq*. And this reasoning leads us to a final representation of *flexibility* based on the “energy spent on imbalance”.

To do so, lets notice that equation (3) can also be written in the following form:

$$(Q_{out} / dT_{out}) - (Q_{in} / dT_{in}) = 0 \tag{7}$$

what, considering again $dT_{out} = dT_{in}$, leads to:

$$(Q_{out} - Q_{in})/ dT_{in} = 0 \tag{8}$$

which is another way of representing the EQUILIBRIUM function for the inventory and can be though as an “Imbalance Ratio”, measured on inventory units (SKU) per unit of time. This already corresponds to a certain “energy” spent per unit of time, and thus gives us an idea of the “*Power Spent on Imbalance*” or *rigidity*, which in fact can be seen as the inverse of *flexibility*. By this definition, the system is more *flexible* when its *rigidity* gets low, and a simple way to measure it will be integrating the EQUILIBRIUM function over time and divide its value by the total time of imbalance. Thus, if for a certain period of time $dT_{in}[j]$ it holds that there was $Q_{in}[j]$ units of material going into the node and $Q_{out}[j]$ units of material going out, the *rigidity* can be calculated as:

$$RIGIDITY = \frac{\sum_j Qin[j] - Qout[j]}{\sum_j dTin[j]} \tag{9}$$

And then,

$$FLEXIBILITY = \frac{1}{RIGIDITY} \tag{10}$$

It is based on this measure the matrix of *rigidity* of a simulated case will be presented later in this paper.

## 4. Multi-function *flexibility* of a single-node system

Even considering a single node system, it is important to remember we are suggesting only a way to measure the inventory *flexibility* in respect to demand variations. Anyhow, in any general single-node system one have to consider a set of output functions *OUTj(t)* being driven by a set of input functions *INi(t)*, all of them running along a certain independent variable *t*, as depicted in figure 5. That is, we must start with the assumption that any of these functions can be graphically represented in time by some

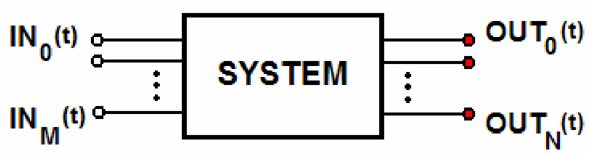


**Fig. 5** Generalised multi-function model of a single node system

kind of graph.

Observing this figure, it can be easily understood that in general one talks about flexibility of the *OUTj(t)* functions in respect to variations of the *INi(t)* functions. If for instance a generic output function *OUTk(t)* is dependent on the generic input functions *INa(t), INb(t)* and *INc(t)*, then one will be automatically able to talk of more than one *flexibility*, as at least the following three obvious types could be considered:

a) *flexibility* of *OUTk(t)* to variations of *INa(t).*

b) *flexibility* of *OUTk(t)* to variations of *INb(t).*

c) *flexibility* of *OUTk(t)* to variations of *INc(t).*

This means in general one will talk about *flexibility* of a *property* in respect to variations of a certain *factor*. If that *property* depends on many *factors*, then many *flexibilities* can be considered for that *property*. To turn the things even more complex, one could also think on the input crossed variations…

So, even being the *flexibility* a simple concept, it usually turns complex if accuracy is important and if the output functions are dependent on more than a single input. This explains why till now many authors try to classify *flexibility* following the different levels strategy proposed by Leslie K. Duclos (2000), where he obviously assumes *flexibility* is a multi-dimensional construct[3].

At the same time, from the point of view presented here, the general *flexibility* of a node will no longer be a *scalar* but a *matrix* connecting the *equilibrium functions of the properties (outputs)* to the *factors (inputs)*. The *flexibility* of a general single node system must then be represented by:

$$FLEXIBILITY = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1M} \\ f_{21} & f_{22} & \cdots & f_{2M} \\ \cdots & \cdots & \cdots & \cdots \\ f_{N1} & f_{N2} & \cdots & f_{NM} \end{bmatrix} \qquad (11)$$

Where $f_{ij}$ is the individual *flexibility* of the *OUTi(t) property* in respect to variations of the *INj(t) factor*. Each of the $f_{ij}$ values can be quantified as long as for each *OUTi(t)* one will establish a way to compute the respective EQUILIBRIUM function and a way of exciting it with the appropriate *input step*. In each case the big challenge is to define the EQUILIBRIUM function. What is this function for the *costs*, for example? Is it easy to describe? And for many other terms of the Supply Chain?

## 5. **N nodes** *flexibility* **(the supply chain flexibility)**

But practical systems are most of the times more complex than a single node system, and when talking of Supply Chains the complexity usually rises. We have shown in the previous section that in general the *flexibility* of a node would be represented by a matrix, from what follows that the *flexibility* of a group of nodes would be a matrix of matrices, and thus something too complex to easily be handled in practice. However, if we are only interested on a particular component of its output vector, that is, on just one output function (the *inventory*, for example) and consider it only depends on a variable (the *demand*, for example), the node *flexibility* already can be reduced to an easier measurable *scalar* quantity. For simplicity, we will assume each node is represented by such a simplistic model.

In that case, the Supply Chain is then reduced to a collection of *inventory* nodes, each one with a certain *flexibility* dependent on its previous element (the supplier) as well as on the reorder quantities. Therefore, the *flexibility* of the overall Supply Chain (in respect to a certain *demand* pattern) is again a matrix where the individual flexibilities will be plotted.

As an example to compute some practical results we will use the Supply Chain structure drawn in figure 6, which represents the "*Cranfield Blocks Game*"[4], a management game developed by Richard Saw (2002)[5].

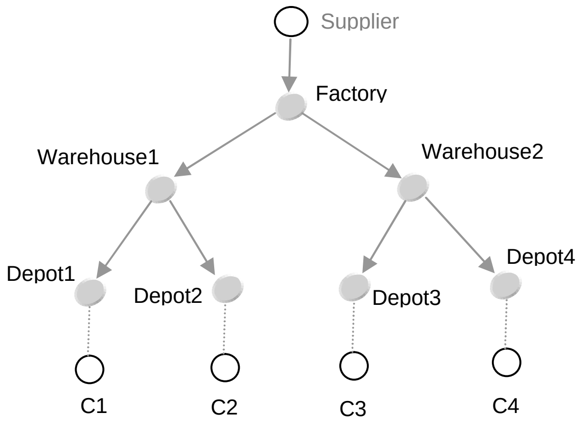


**Fig. 6** Structure of the "*Cranfield Blocks Game*"

This is a seven node Supply Chain (from *Depot1* to the *Factory*) where the *direct demand* (*inputs*) from *customers* (*Cj*) is injected at the depots level, and the *Supplier* is considered an infinite source of materials. For simplicity, only one product is being considered.

From what concerns our interests this can be thought of a system with four (4) inputs driving certain output functions at each of its seven (7) nodes. Thus, by means of injecting steps of demand at each input, one will be in principle able to measure how each node functions (like inventory, costs, etc.) will respond to such "shocks", and through such measure represent the correspondent overall *flexibility* matrix.

In general, a simple way to write down this matrix will be plotting the individual flexibilities in columns ordered by increasing level of the facilities on the chain, as next figure suggests, which fast let us to have an idea on how the chain is susceptible to input "chocks", as it will be shown in a simple example presented soon.

| | | inputs | | | |
|---|---|---|---|---|---|
| | | **c1** | **c2** | **c3** | **c4** |
| level 1 | **dep1** | $F_{11}$ | $F_{12}$ | $F_{13}$ | $F_{14}$ |
| | **dep2** | $F_{21}$ | $F_{22}$ | $F_{23}$ | $F_{24}$ |
| | **dep3** | $F_{31}$ | $F_{32}$ | $F_{33}$ | $F_{34}$ |
| | **dep4** | $F_{41}$ | $F_{42}$ | $F_{43}$ | $F_{44}$ |
| level 2 | **ware1** | $F_{51}$ | $F_{52}$ | $F_{53}$ | $F_{54}$ |
| | **ware2** | $F_{61}$ | $F_{62}$ | $F_{63}$ | $F_{64}$ |
| level 3 | **factory** | $F_{71}$ | $F_{72}$ | $F_{73}$ | $F_{74}$ |

**Fig. 7** General *flexibility* matrix for the "*Cranfield Blocks Game"*

Following this representation, the *flexibility* of the chain will be the *flexibility* of its "arms" connecting the *last customers* to the *primer suppliers*. Thus, it is somehow understandable that a particular Supply Chain would show high flexibility on serving certain customers and at the same time exhibit disastrous flexibility on serving others. A nice result from this approach, however, is that "*the flexibility of an arm will be extremely dependent on the flexibility of its slower node*", since the speed on a chain is the speed of its slowest element, what means it can sometimes be very important to ensure a good cooperation between partners in the Supply Chain.

### 5.1 *The Inventory-flexibility-to-demand*

Following these ideas, we now present the determination of the *Inventory-rigidity-to-demand* matrix for the "*Cranfield Blocks Game*", achieved by simulation. For convenience, we will use the *rigidity* representation, as it always deals with finite quantities.

In this case, all the facilities on the game have been configured to use the *(r, Q)* stock reorder policy and the demand at each *Depot* have been initially kept constant at the average value the manual version of the game states. Anyhow, at a certain moment of the simulation process, the demand of a certain *Depot* received a sudden increment on its value, and the new situation was maintained till the end of the simulation. This procedure was done in each of the *Depots* separately. In each case, it was measured at each node of the Supply Chain the *rigidity*, applying the equation (9), and then the matrix represented. Also to simplify the read of the results the null values have been substituted by dashed lines in the matrix. For the simple propose of this paper, each simulation have been executed with only 3 replications, but the averages and irrespective uncertainties have been computed for 95% confidence as if more than 20 samples would have been used.

At the figure 8 is represented how the stock level of *Depot1* behaved when subjected to a demand step of 2.5 times its usual average value. Notice that even if the system is answering good to such requirements there was introduced on it a certain instability that did not exist before.

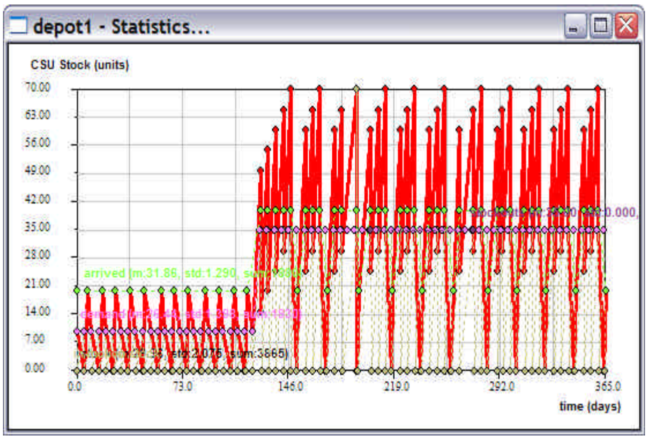


**Fig. 8** Behaviour of *Depot1* stock level in reaction to a demand step

In the next figure (fig. 9) is represented the behavior of the EQUILIBRIUM(t) function for the same *Depot1* as it is described by equation (4). We opted to use this form of presenting the equilibrium to the user once it is more interesting to plot graphically than the one resulting from equation (7). From this figure is already evident that a certain instability have been introduced due to the abruptly change of demand. This instability, however, is mainly due to the lack of an integer relation between the new demand and the quantity ordered to the supplier. By readapting this quantity one could easily reduce this kind of instability. This also lets us induce that different reorder policies can conduct to different *flexibility* values.

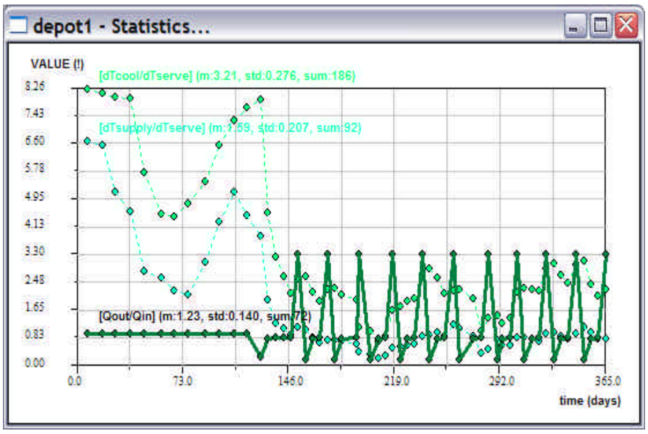


**Fig. 9** EQUILIBRIUM(t) function of *Depot1* under a demand step (bold line)

It comes also obvious from this figure that the "*Time to Recover Equilibrium*" (*Tq*) would be difficult to compute in cases like this, once the system does not stop to oscillate. Nevertheless, to measure the RIGIDITY using the second approach (as it is used here) eliminates this problem and stabilizes the measure independently the time of the window of observation.

And finally, in the figure 10 we present the RIGIDITY matrix for this case, resulting from the four simulation processes, each one of three runs. Al the values presented are in SKUs/day.

| | | inputs | | | |
|---|---|---|---|---|---|
| | | c1 | c2 | c3 | c4 |
| level 1 | dep1 | 4.6 ± 0.3 | ---- | ---- | ---- |
| | dep2 | ---- | 8.5 ± 0.8 | ---- | ---- |
| | dep3 | ---- | ---- | 13.6 ± 0.6 | ---- |
| | dep4 | ---- | ---- | ---- | 6.7 ± 9.0 |
| level 2 | ware1 | 1.6 ± 0.0 | 3.9 ± 0.6 | ---- | ---- |
| | ware2 | 5.0 ± 0.4 | 5.0 ± 0.3 | 7.4 ± 0.7 | 6.5 ± 6.4 |
| level 3 | factory | 4.6 ± 2.4 | 5.2 ± 1.3 | 4.6 ± 0.7 | 5.6 ± 1.6 |

**Fig. 10** General RIGIDITY matrix for the "*Cranfield Blocks Game*"

It is of course important to notice that this matrix is valid for certain specific conditions, and so those conditions must be well specified before interpreting the data. In this case, the conditions could be roughly represented by:

*All Step Demand Amplitudes = 2.5 x (usual average demand).*
*All Reorder Policies = (r=ro, Q=Qo), as the game stated.*
*Each facility fleet = 1 vehicle Van.*
*All Depots start from EQUILIBRIUM.*
*Etc.*

### 5.2 *Interpreting the matrix*

It is now clear from this matrix that a step on demand of amplitude 2.5x on the *Depot1* will let us observe a "*Power Spent on Imbalance*" of 4.6 SKU/day in this facility, as well as 1.6 SKU/day at the *Warehouse1*, 5.0 SKU/day at the *Warehouse2* and 4.6 SKU/day at the *Factory*. For instance, it can also be expected that the same kind of step at the *Depot3* will lead to a much higher *rigidity* at that facility as well as to a higher influence on the *Warehouse2*, which will exhibit 7.4 SKU/day of imbalance. Anyhow, such a step on *Depot3* will never influence *Warehouse1* behavior. And so on…

Another interesting aspect one can infer from this matrix is that probably the imbalance of 5.0 SKU/day shown by *Warehouse2* is not motivated by the steps, as it maintains almost constant on the cases C1 and C2. This is probably a residual imbalance due to the natural uncertainty on the *Warehouse2* demand due to unsynchronized *Depot3* and *Depot4* reordering moments.

A last interesting aspect coming out from this data is that it was impossible to obtain a reliable value on the C4 case, as the uncertainties are of the same order of the averages. And in fact, as the next figure shows, it was observed such a high *stockout ratio* on *Depot4* that hardly it could lead to reliable values for the *rigidity*.

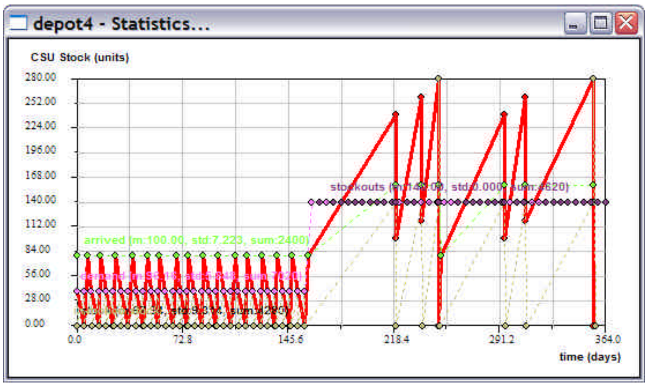


**Fig. 11** Stock level and stockouts at the *Depot4* facility

This also have been confirmed by the "Satisfaction ratio" observed at the customer C4, presented in the figure 12, which have dramatically rolled down after the "chock" of demand.

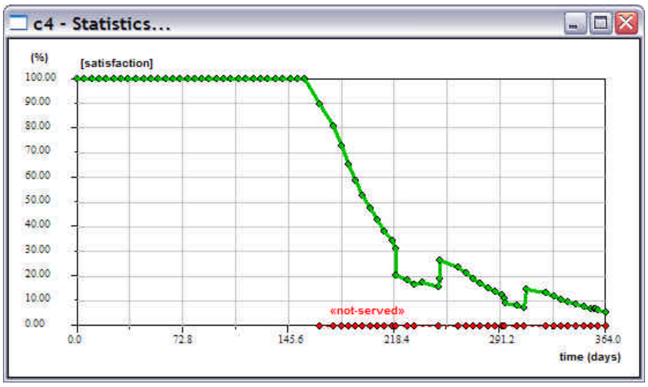


**Fig. 12** "Satisfaction Ratio" at the C4 customer

Based on this case, a deeper study concerning the *flexibility* dependency on reorder policies, reorder levels and step amplitudes will be published in a paper to come.

## 6. CONCLUSIONS

This results, achieved with the help of simulation, let us conclude that the proposed methodology to measure *rigidity* in a Supply Chain is feasible and the results can be somehow easily interpreted, therefore conducting to the possibility of applying a reasoning and, trough it, to support decisions.

At the same time, we also conclude that *flexibility* depends more on the suppliers than on the customers, which automatically remind us the idea of good <u>cooperation</u> with suppliers. It seems also natural *flexibility* results form an interrelation from where concepts as <u>cooperation</u>, <u>visibility</u> and <u>trust</u> automatically flow. At the same time, it have also been shown that *flexibility* can depend on the resources used and on how they are used, like the number of vehicles dedicated to delivery, for example, or the model used for reordering the material.

Of course that it is obvious the *flexibility* can be potentially made higher if working with more than one supplier, using redundancy, the usual way to think on flexibility, but that does not give the manager any quantitative values for reasoning, as it is no more than a holistic proposal, forgetting that more than a supplier can imply serious difficulties in relationship, due to concurrence.

Finally, one must remember that the present results have been obtained considering only "positive" steps of demand, that is, incrementing it, and nothing have been said for the opposite case, when there is a sudden decrement on demand. Anyhow, as the usual Supply Chain is mainly a flow of products in only one way, it results a natural true the best approach on theses cases it is to maintain the minimum stock possible, which in the limit would be a single unit of material (JIT).

Future research on this matter could include studies about other kind of Supply Chain structures, not only didactic but also representing real systems, and, using the kind of analysis we presented here, enrich the knowledge about the idea of *flexibility* with the final intent to turn it more scientific that what in fact seems at the moment. Testes could be made about *flexibility* on many aspects of the Supply Chain, as for instance with different reorder policies, or demand amplitudes, as well as with diverse resources and policies related with transportation, or even other. This seems, in fact, an open field for tests using simulation.

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# Distributed Application for Supply Chain Management Training

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KEYWORDS: Supply Chain, management games, "*Bear Game*", inventory policies, "*Bullwhip Effect*".

## ABSTRACT

Here we present a computer application planned to be used as an interactive tool for Supply Chain Management Training. Implemented with Visual C++, this application embeds the "*Cranfield Blocks Game*" (Richard Saw[1], 2002) network structure, and uses precisely the same demand patterns as the manual version of the game. Anyhow, instead of reducing the play to 12 reorder cycles, as the manual version does, this application extends those patterns throughout the time till any number of reorder cycles, what let the results become more useful and interesting even for didactic purposes. At the same time, the present application substitutes the classroom table by the computer screen, and can be made to run in AUTOPLAY mode, meaning the game can also be played with only one player or even automatically, with no players at all. In a certain way, this comes closer to some kind of Distributed Supply Chain Simulation, apart from the fact each lead time is fixed, as the "*Cranfield Blocks Game*" states, and the AUTOPLAY stock policy is empirical.

As each application communicates with the SERVER using the TCP/IP protocol, the players can be spread by different computers and even placed at different geographic locations if connected to the INTERNET.

In the end of this paper, results achieved with an automatic running session and with the involvement of a group of students from the *Escola de Gestão do Porto* (EGP)[2] will be presented and compared.

## 1. Introduction

Interactive Games are nowadays being used as powerful tools to exercise the ability of people to manage a wide range of complex systems, from flight simulation to the control of the flow of water in dams under extreme conditions of raining, for example. Following such a tendency, Supply Chain Management also started to apply those techniques to improve the ability of the managers to resolve faster and more efficiently some problems they are expected to face in the real world. Training before to fit later is the philosophy of such an approach.

Related to the sciences of management one can already find games like the *International Logistics Management Game*[3] *(ILMG)*, the *Corporation: A Global Business Simulation*, the *BEEFEATER RESTAURANTS MICROWORLD*[4], as well as the *GOLDRATT'S GAME*[5] and many others, but it seems one of the oldest and most popular directed to Supply Chain Management is the "*Beer Game*", conceived at MIT in 1960 (Sterman1989), with which the *Bullwhip* effect (amplification of demand at the upper levels of a Supply Chain) have been observed, as well as the importance of communication between partners stated. Many of those games, however, are still being widely used as manual tools. The "*Beer Game*", for instance, can still be bought inside a box in which one will find written instructions, some other pieces of paper and some more little blocks representing the material units used for stocking. Nevertheless, at the moment it is also possible to play the "*Beer Game*" electronically, after David Simchi-Levi[6] and Phil Kaminsky[7] developed their *Web Based Beer Game*[8].

In fact, there are some inconvenient features on presenting management games in traditional manual form, being the most significant: (1) the space required to play the game; (2) the need of an extremely well organized *manual* communication scheme between partners, by which time synchronization will be ensured (usual the job of another person); (3) the usage of paper cards to communicate demands; (4) and the non existence of a common support where the overall supply chain behavior can be easily shown and seen by all the members, during the game or at its end. The record of stock data and the computation of other decision variables are also time consuming in the manual version, and can be highly improved using a computer application. The present application, focused on the the "*Cranfield Blocks Game*", and named "*SCGame(cranfield)*", has as the main objective to give the players such advantages.

Once it uses a CLIENT-SERVER technology, this application has been divided in the applications "*SCGame(cranfield)_server*" and "*SCGame(cranfield)_client*". We will present each of them in this paper.

## 2. The "*Cranfield Blocks Game*"

The original "*Cranfield Blocks Game*" uses a multi-level structure to represent the supply chain, thus being a more general game than its counterpart "*Beer Game*", which usually looks at the supply chain as a linear structure. Nevertheless, the primary idea of the "*Beer Game*" is maintained, and one could say the "*Cranfield Blocks Game*" can also be seen as a more complex version of the former.

The structure of the "*Cranfield Blocks Game*" (Fig. 1) is based on four *depots* (retailers) that are connected to two central *warehouses* and these warehouses connected to a single *factory*, which in turn is served by an ideal *supplier*. The intent of this configuration is to let the players have a better sense of some of the behaviour that stands for real supply chains, at least concerning the need to fulfil the demand of more than just one customers in each facility, and how such a need can already introduce a significant variability in the demand, turning more difficult to establish the optimal management policy, even when only one product is considered. That is the case of the game. As well, this configuration lets the results give an idea on how the response of the chain depends on the demand amplitudes, as different demand amplitudes are previously "established" at the last customers, directly connected to the depots.

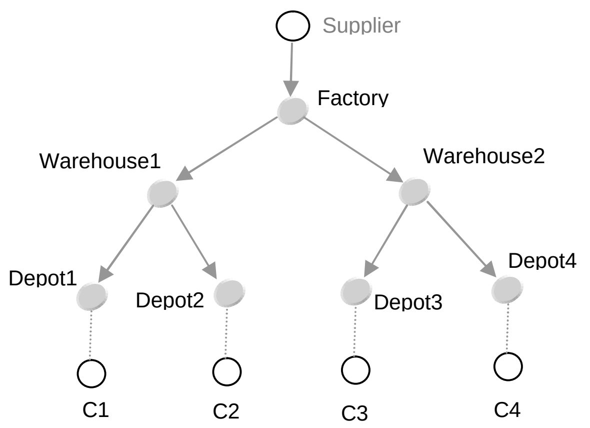


**Fig. 1** Structure of the "*Cranfield Blocks Game*"

Usually, this game is played with seven groups of students, each group being responsible for the management of a single facility. The customers demand (*Cj*) are random generated, and the supplier (up on the figure) is considered an infinite source of materials. Thus, the student groups are only endorsed to manage from the *Depot1* to the *Factory*. No backorders are considered, and each facility must adjust its reorder quantity to a multiple of a certain *Base Quantity* (BQ) established at the beginning of the play and which increases from left to right and as the facility approaches the *Factory*. All the activity in the chain begin with the demand of products from customers (*Cj*), and the goal of each facility manager is to <u>fulfil demand keeping the *stock* as low as possible without incur in *stockouts*</u>. The average costumers demand amplitude also increases from left to right in the chain, meaning *C1* < *C2* < *C3* < *C4*.

The initial conditions of the game are the following:

| Facility: | Demand | Initial Stock | Reorder (BQ) |
|---|---|---|---|
| Depot1 | C1 | 40 | 20 |
| Depot2 | C2 | 60 | 50 |
| Depot3 | C3 | 40 | 40 |
| Depot4 | C4 | 100 | 80 |
| Warehouse1 | … | 120 | 100 |
| Warehouse2 | … | 200 | 120 |
| Factory | … | 200 | 200 |

**Fig. 2** Initial conditions for the "*Cranfield Blocks Game*"

And the original customers demand patterns for the 12 cycles of the manual version is:

C1 = 20, 0, 10, 20, 20, 20, 10, 20, 0, 0, 20, 20.
C2 = 30, 40, 10, 20, 40, 50, 40, 10, 20, 50, 40, 30.
C3 = 30, 30, 30, 40, 20, 10, 10, 20, 30, 10, 30, 20.
C4 = 10, 50, 30, 50, 60, 50, 20, 30, 10, 20, 50, 40.

These patterns will be maintained in the computer version precisely till the 12[th] cycle, but then they will be replaced by patterns generated based on random normal distributed numbers. This aspect was strictly preserved, for that results achieved with the computer version could be compared with the results obtained with the manual version.

Finally, in order to be able to compare the management of different facilities, there was introduced a classification in the computer version that probably can diverge from the criteria used by the father of this game. For our own purpose we decided to classify the management of each facility by the following criteria:

CLASSIF = 100 x (*totalDemand* – 1.5 x *totalStockouts*) / *totalArrived*

Were *totalDemand* represents the amount of demand at the end of the game, *totalStockouts* represents the amount of *stockouts*, and *totalArrived* represents the amount of material arrived from the supplier. Thus, this classification pretends to give an idea or the efficiency of the management, assigning a negative weight factor of 1.5 to the *stockouts*.

## 3. The CLIENT-SERVER application

To implement this game we have developed a CLIENT-SERVER application communicating by TCP/IP, being the SERVER the responsible for the customers demand generation, the initialization of the game, the synchronization and control of time and the communications between partners, and the CLIENT being the interface each manager has to play and manage the stock resources of his facility.

Before the beginning of the game, the SERVER (Fig. 3) must be launched in the Operating System (WINDOWS) for that it will wait for the clients to ask permission to connect. As each client asks this permission, the SERVER will assign to it a free facility,

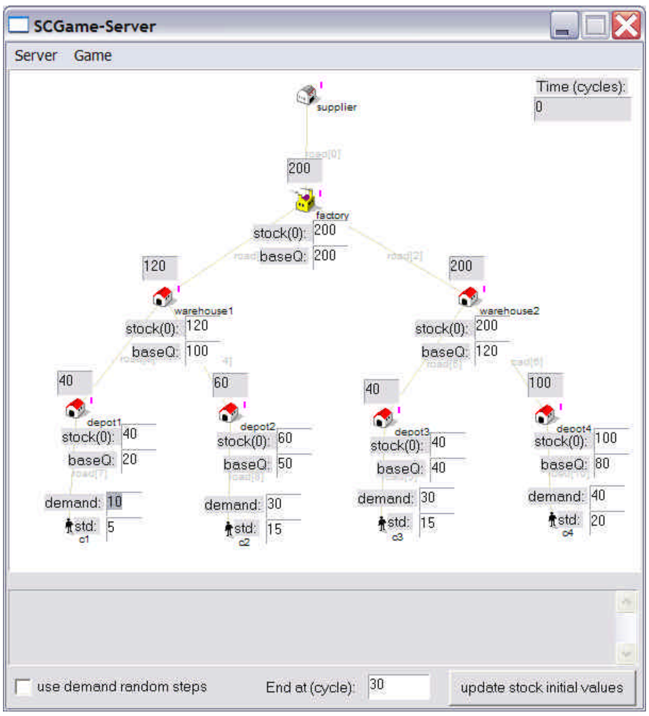


**Fig. 3** Supply Chain SERVER "*SCGame(cranfield)_server*"

and will refuse any connections once the supply chain is complete. In that moment, the SERVER will then send a message <u>*msg::play*</u> to each CLIENT, to signal the game can be made to start. The time will only advance to the next cycle whenever all the CLIENTS have played the present cycle, thus ensuring the synchronism between them is maintained.

The SERVER is the centralised controller of the game. It not only establishes the access to the players and ensures the correct time holds for all of them, but also it controls the flow of demand between partners. This is achieved by the simple exchange of messages between the SERVER and the CLIENTS.

As it can also be inferred from the previous image, this version can be made to run for longer periods of time than the original 12 cycles, as well as it allows the initial stocks of the facilities, their *Base Quantities* (BQ) and the customers' demand to be modified, even if actually they will start with the values of the manual version. Finally, this computer version gives the manager the possibility to introduce "random steps" of demand at each customer's demand site, what probably can be used to train reactions to high instable markets, or even to make experiments concerning the flexibility or the agility concepts.

As the game runs, it will also be possible to make an idea of the overall supply chain behaviour, once the stock of the facilities can be shown graphically to the user, as the example of figure 4.

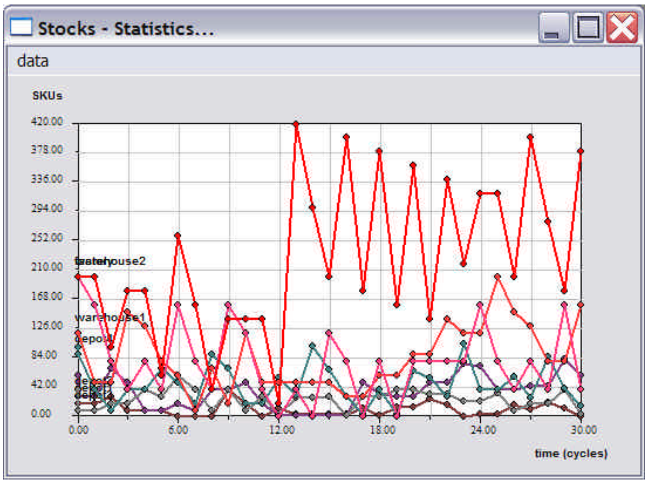


**Fig. 4** Example of the stocks of facilities shown at the SERVER

As suggested in the next figure (Fig. 5), the game can be usually played in a room with each group of students around a computer, while the SERVER runs in another computer nearby, many times with its display projected in the wall as a way to let the groups access the evolution of the supply chain data, mainly

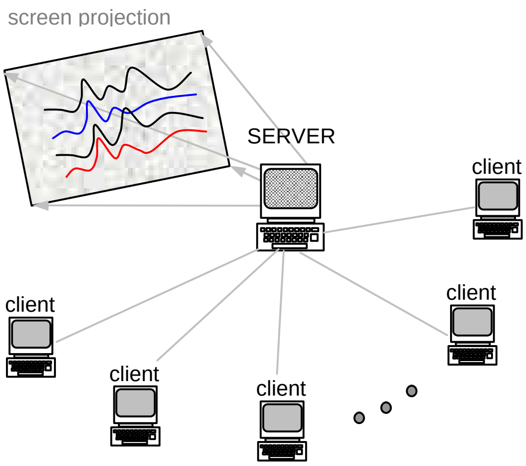


**Fig. 5** Example of a simple apparatus to play the game

the stock levels of the partners. Anyhow, the game can also be played by internet if the SERVER is previously running in a reachable address.

On the other hand, the CLIENT application is the tool with which the groups manage their facilities, as well as they communicate the demand to their suppliers and serve their customers requirements. This application, less complex than the SERVER, is the real player's interface, and can be made to run in any location of the computer network as long as it will be able to reach the SERVER by TCP/IP.

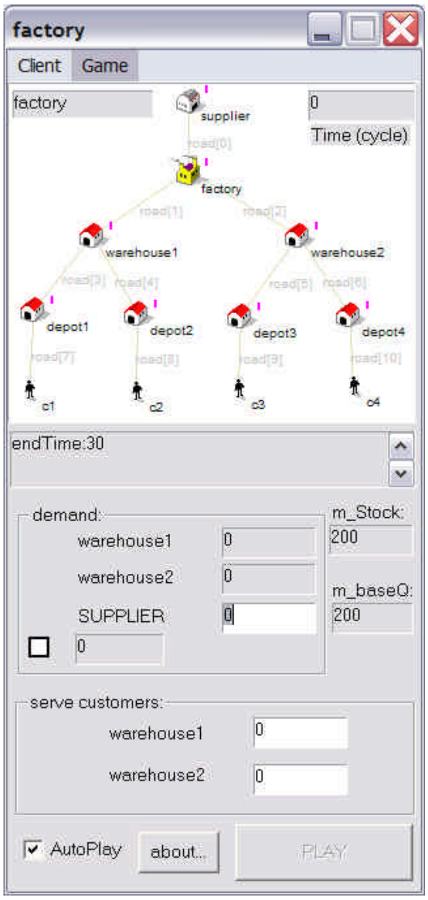


**Fig. 6** The *SCGame(cranfield)_client* in this case assigned to the Factory

All the CLIENTS have the configuration shown in the next figure (Fig. 6), and differ from each other by the natural amounts of stock and BQs, as well as by the facility name and the designation of their customers and suppliers. The figure shows a CLIENT assigned to the *Factory*.

To help the player to locate better its facility in the supply chain, this application uses an image of the network where all the facilities are represented. Also there is a window where messages coming from the SERVER are displayed, and a check button of *AutoPlay* which lets the application react automatically to the customers demand and decide when to order new material. In any case, the criteria used on those decisions are empirical and do not follow any of the models known in practice for stock control, as the intention was to use this application to simulate the kind of "empirical" behaviour many times used in the practice for managing small stock resources.

At the same time, the CLIENT application has two other *zones* very important to the player, shown in figure 6: the *demand zone*, where demand from *customers* is continuously updated and the demand to the *supplier* affected, and a *serving zone*, where the user can fulfil the requirements of material to send to the customers. These operations will be executed when pressing the PLAY button, which

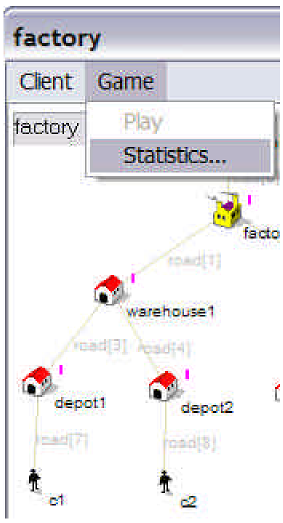


**Fig. 7** Menu Statistics

then will automatically be disabled by the application and still in such state till the next time the SERVER will enable it, meaning this facility is again allowed to play.

Another feature concerning this CLIENT application is the possibility of tracking some important parameters during the game, as it is the case of the *stock*, the *demand*, the quantity *arrived* form the supplier, and the *stockout* level, what usually helps the player on making better decisions. This data will be presented in the form of a graph that will appear next to the CLIENT application as long as the menu option *Game->Statistics* is chosen (Fig. 7). A graph of this type, related in the case with *Depot1*, is shown in the next figure (Fig. 8).

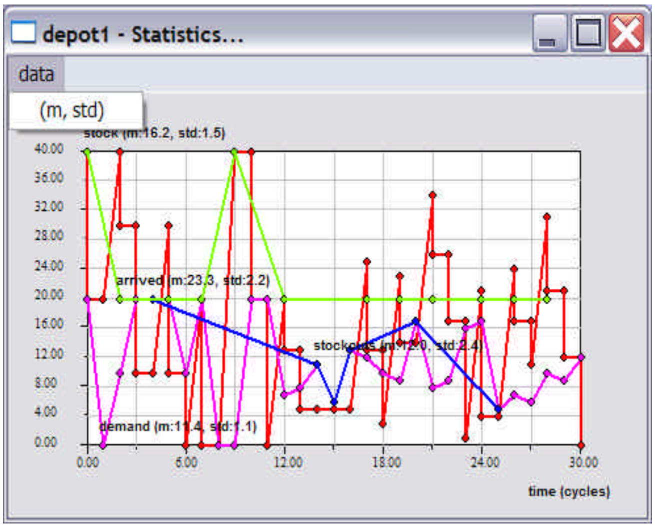


**Fig. 8** Graph of *Stock*, *Demand*, *Arrived* and *Stockout* level

In addition to the visualization of these parameters, the player can use the menu option *data->(m, std)* of this window to automatically compute the average value and standard deviation of each of the data series represented.

## 4. RESULTS AND COMMENTS

As was said earlier, the results presented in this paper have been obtained in two sessions. In the first session the game was made to run automatically with all the facilities in AUTOPLAY mode, during 30 demand cycles. In the second session the game has been played by seven groups of students attending a Masters Course at the *Escola de Gestão do Porto* (EGP), and also run during the same 30 cycles.

In each case, data like the one showed in figure 8 was collected for each facility, and then its average values, standard deviations and accumulated values have been computed, as well as the final classification of the facility. These computed results were then recorded and handled in an EXCEL spreadsheet for the two separated sessions, in order to make the comparison between them easier. Notice that the unity of stock used here is the SKU, worldwide known as *Stock Keeping Unit*.

Different kind of calculations could be made based on the row output data retrieved from the game, but for our purposes we decided to present only some results based on averages and on standard deviations. Averages will give us the sense of how each facility was in general handling the interesting parameters, while the standard deviations will lets us have an idea about the variability observed on handling those parameters. Based on such simple results we expect already to be able to conclude about the interest of the present application tool.

In figure 9, for instance, the *average values* of those parameters are represented, computed after the game have been played the first time by the students. It shows that even if the final classification of the management of the facilities exhibit an almost flat behaviour, it was also observed an obvious tendency on the other parameters (except the demand, of course, due to be an input) to grow from the left to the right of the supply chain network, as well as when approaching the *Factory*. This is precisely the tendency induced in the system by the differences in the BQ quantities, as we have stated earlier. Thus, due to the fact these results tend to be proportional to the respective BQ of the facility, is seems all groups have used the same kind of empiric reorder policy, as well as it seems they have faced the same challenges on managing the facilities.

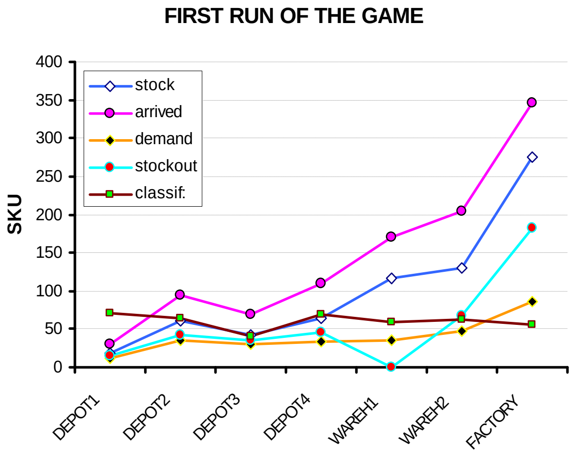


**Fig. 9** Computed results obtained on the first Students Session

These results can be compared with the data obtained with the AUTOPLAY session, which is represented in the next figure (Fig. 10), where all the facilities were using precisely the same stock control empiric policy, previously established by us.

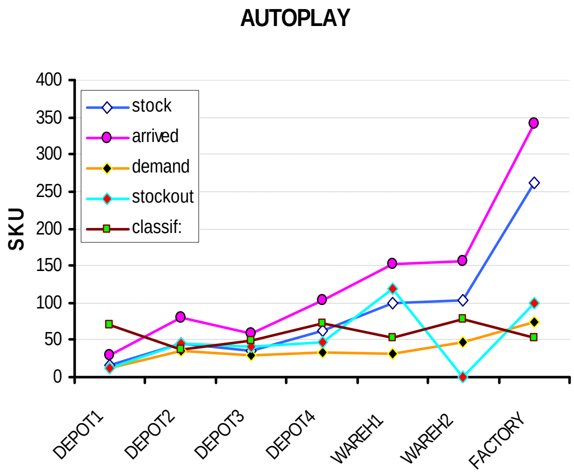


**Fig. 10** Computed results obtained with AUTOPLAY Session

Although the various parameters seem to have improved slightly in the AUTOPLAY case, as well as the level of *stockouts* have been reduced, the two cases show a similar tendency to follow the induced BQ differences. Maybe this would mean that to manage this system in an empiric base few differences would arise due to the "experience" and the "quality" of the manager. In fact, in the two cases de classification parameter is maintained practically constant at all the facilities.

However, when we compare the variation observed in the two sessions by means of the standard deviations charts, shown in figure 11 and figure 12, a significant difference is already noticed. It seems obvious the "experienced" manager (AUTOPLAY) would be able to handle the facilities in a much more smooth way than a beginner. In fact, in the AUTOPLAY the variability of the *stockouts* was drastically reduced at the *warehouse1*, *warehouse2* and *factory*, as well as the amount of material ordered, even if not as drastically.

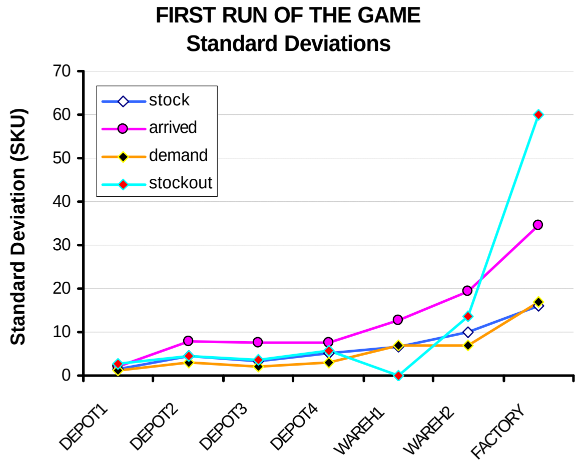


**Fig. 11** Standard Deviations at the first Students Session

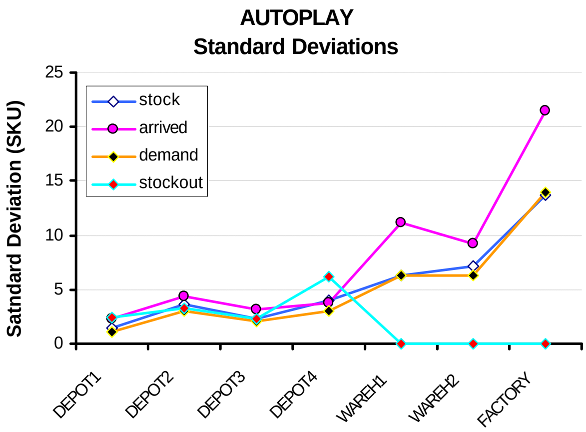


**Fig. 12** Standard Deviations in the AUTOPLAY Session

Other measures could be achieved with this application, as it gives the user a wide range of untreated output values over time, so making the experiments of management dependent on the imagination of the game's supervisor. Also, as this game lets the players visualize and record the evolution of important parameters with the time, even testes concerning the *visibility* or *not-visibility* between partners can be made, depending whether the overall supply chain is projected or not-projected on a wall, where all the stock levels can be turned visible to every partners.

## 5. CONCLUSIONS

Based more on the potential of this application than on the results presented here (these are just an illustration of such a potential), we conclude this computer application represents an interesting tool for Supply Chain Management Training. In fact, the results achieved with the manual version can also be obtained using this tool, and in addition other interesting aspects are made available, like the portability and the flexibility of a distributed computer application, the capability of considering *visible* or *not-visible* scenarios, as well as the introduction of demand steps at the ultimate customers, which we imagine can be useful in future testes concerning studies of *Flexibility* or *Agility*, for example.

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[7] Professor at the Industrial Engineering and Operations Research Depart., University of California

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# An Approach for Dynamic Supply Chain Modelling

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## ABSTRACT

This paper presents some concepts related with the development of a "model generator" for simulating supply chain systems. Such concepts arise not only from the object point of view taken over this system, but also from our intention to synthesise the behaviour of such kind of systems in a more general form, in particular concerning the events and activities related with *suppliers*, *factories*, *warehouses*, *retailers*, and even the last *customers*, which in fact trigger the flow of materials and information on the chain.

Unlike the static approaches usually used for strategic purposes, where parameters like the time of delivery or the average rate of material flow are held as inputs to the system, the ideas described here consider a dynamic representation of the supply chain in which those parameters are *results* of some detailed simulation process, what gives this approach the ability of modelling those systems starting from the less abstract point of view to a more abstract representation. The result is a more realistic picture of the dynamics involved.

Due to this fact, this approach could be seen as being more directed to managers than to strategists. Nevertheless, the objective is also that the models can be used to simulate either short or long periods of time, revealing their usefulness also for strategic analysis.

The basis of these ideas is to consider the flow of products, information and money between any elements in the chain as a general form of *customer-supplier* exchange activity, and also by treating each of those elements as inheriting from a single element which includes the basic behaviour (and resources) of a *factory*, *warehouse* and *retailer*. A description of such element will be made, explaining its structure and the associated *fixed* and *variable* costs of its various processes.

As we will see, many parameters considered inputs to other modelling techniques will appear here as outputs, giving the analyst more interesting data with which it can measure the supply chain performance by means of any statistical methods.

## 1. Introduction

During last decades, most of the simulation approaches used to model the supply chain have been deeply related with strategic intents, that is, were mainly devoted to study the problem of dimensioning and geographically positioning the chain components in a way the overall expected costs could be calculated and, maybe, optimised. The objectives of such approaches were mainly strategic, and so, dealing with average values over long periods of time. In a certain way, the intent of those models was to turn the results independent of *time* variable, and so, what one can retrieve from them is also a static expectation. Although these methods still are very important on the first step of a chain establishment on the ground, they cannot give confident results that could help to manage the supply chain, that is, they hardly would survive to the need of characterizing the chain dynamics, or optimising week-by-week the processes developing in it. To try to resolve this kind of issues, the supply chain started to be also modelled in a dynamic way, and the approach presented here must be considered one more perspective to enrich such trials.

In the point of view of this approach, the supply chain is already established on the ground and the problems to be studied or analysed must be related with the optimisation of the actual processes running in the chain. These processes are mainly the *purchasing*, the *stocking*, the *manufacturing*, the *delivering* and the *managing*; all of them will be measured using not only technical but also economical indexes. This last aspect will be included as a way to measure the economical performance of each element, being also very useful when the chain contains elements belonging to different enterprises, that is, when there is concurrence between different management systems implanted on the same ground. By simply representing the flow of money, one can visualise and easily calculate the *costs* and the *income* for a particular group of elements on the chain, and so, also for those one considers its own part of the system...

As showed in figure 1, in general the supply chain is considered a kind of network connecting *factories (F)*, *warehouses (W)* and *retailers (R)*, with these elements treated as having different structures and different behaviours on the

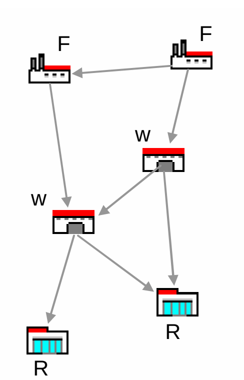


**Fig. 1** General concept of a supply chain

processes running in the chain. In the *factory*, for example, there is a transformation process that gives the row materials the aspect of products, while in a *warehouse* there is only storage and handling processes and in the *retailer* only the action of sales. Finally, what flow in the net are products, transported by vehicles.

Here, however, elements like *factories*, *warehouses* and *retailers* are considered inheriting from a single element that will be named *customer-supplier-unit* (CSU), with which will even be possible to model the figures of the *supplier* and *last customer*. Thus, the overall chain is seen as a group of CSUs connected together by a net of transports, where there also can be exchange of information (fig. 2). Now, what will distinguish a *factory* from a *warehouse* or from a *retailer*, or any other element, will only be how that particular element uses the resources of its CSU and the kind of materials it handles as input and output.

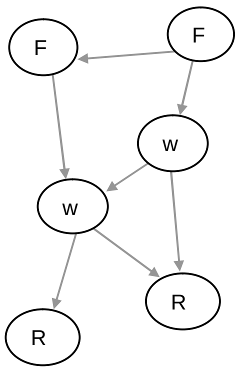


**Fig. 2** CSU equivalent of a general supply chain

Each CSU lives from a constant exchange activity with its neighbours, receiving material and information and giving back money, delivering material and information and receiving money. Thus, in order to see how the economy develops between the elements on the chain, it will be included in the basic structure of the CSU a reference to its own <u>economic account</u>. One must not forget most of the decisions are taken not only based on the technical performance of the systems but also on how the money spreads along those systems… This account, of course, must include *costs* and *incomes*, in a way that with the results of the simulation one can better predict how each of these elements is contributing to the overall economical performance of the chain.

## 2. The *customer-supplier-unit* (CSU)

The CSU is then a basic element who owns a group of *customers*, to whom it delivers material and from whom it receives money, and a group of *suppliers*, from whom it receives material and to whom it returns money. Anyhow, to be able to handle this basic functionality, the CSU must also have in its structure some more general resources. Basically, these resources will be a *stock*, an *economic account*, an *input queue* where the *supplier* vehicles will wait to deliver the materials, and an *output queue* where other vehicles will line up to receive the material that must be delivered to the *customers*.

In order to be able to manage these resources, the CSU must also include in its structure a *list of suppliers*, a *list of customers*, a *list of products* and, finally, a *list of vehicles* representing its own *fleet*. In this approach we established as a principle that <u>the *fleet* always belongs to the one who delivers</u>, what seems a reasonable approach for most practical cases, even when the fleet is hired, as we will see later.

Considering this structure, which is depicted in figure 3, the CSU becomes a general element ready to be linked to other elements of its kind, making possible the overall supply chain representation. Of course, different CSUs can have different amounts of stock, different number of customers and (or) suppliers, different products, and so on, depending on the role

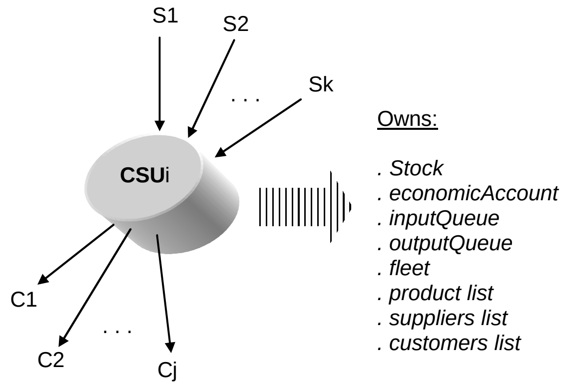


**Fig. 3** Generalised CSU concept having *k* suppliers and *j* customers

they play in the chain. For instance, ultimate customers can be thought as having null stocks, null fleets and null customer list, what will reduce them to a source of money for the chain and a demand of products. On the other hand, a supplier source can be seen as a CSU having infinite stock and null supplier list. Note also that raw materials can be treated as products, even if later will be necessary to adapt the unity of transport to the proper case. Thus, this approach opens the representation also to *last customers* and *suppliers*, which in most of the simulators are treated as simple statistical parameters.

## 3. Connecting the CSUs and the flow of materials

To be able to model the chain dynamics is now necessary to connect each CSU to its effective neighbours. A net of *paths* in which vehicles will move ensures this. These *paths* can include normal roads, highways, railways, boat circuits, and even airlines. However, for didactic purposes, let us assume general-purpose ground vehicles as presented in figure 4.

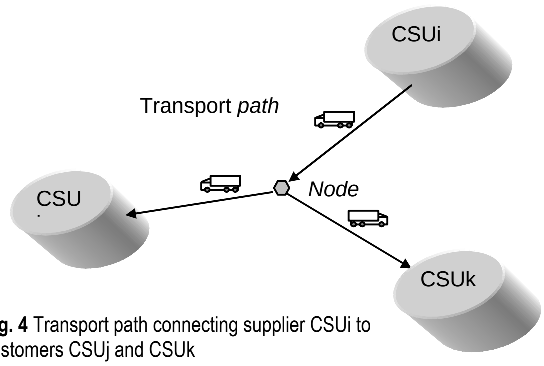


**Fig. 4** Transport path connecting supplier CSUi to customers CSUj and CSUk

Note that each *segment* of a *path* can then represent different costs to the delivery process; for instance, vehicles can first run on a highway and then change to normal roads. That, and the probable existence of real road junctions in practice, implies also the usage of the concept of *node* (fig. 4). Therefore, vehicles will travel from *node* to *node* with the objective of executing a certain predefined *job*. This also means each CSU must include the dimension of a *node*. Of course, as the vehicle moves from one *node* to the next *node* the delivery costs are expected to rise, as they are calculated based on the known costs of the vehicle utilization per kilometre and driver cost per day.

Note also that, in principle, time spent by the vehicles in these *paths* will not be predictable, also because different vehicles from different suppliers can reach the customer around the same time, and then it will be necessary to queue before the effective delivery will take place. Situations like this will be, of course, dependent on the layout of the chain, on the quantity of suppliers serving each customer and on the intensity of delivering flow in the net, as well as on the delivering policy and the size of vehicles.

Each vehicle is treated as an independent entity, and then the movement of a vehicle trough these *paths* will be simply dependent on the vehicle itself, that is, it will result of the execution of a sequence of events that are "property" of the kind of vehicle. Thus, from a high-level point of view, there will be only two commands (events) each CSU can send to its vehicles: *e_startDelivery()* and *e_startReturn()*. The first sent after attributing a certain *job* to the vehicle and the later when a *job* is finished. The vehicle itself must then be capable of delivering the material without any other interference from its CSU, even if a *job* includes more than one delivery point, as in the case of local delivery.

## 4. Delivering speed

After the material is ordered to a particular CSU, it will start a sequence of actions on that CSU that will lead to the *processing of the order*, the *material packing* and finally the start of the *delivery process*. From the point of view of the customer, the speed of the delivery will also depend on the time spent on such sequence of actions and on the criteria used by the supplier CSU to assign *jobs* to vehicles. Over this, however, it must be added the time needed to carry the material along the *paths* between the CSUs, which is dependent not only on the *vehicle speed*, but also on the *limit speed* of each *segment* on the *path* trough where the vehicle must travel. The figure 5 helps to explain better these ideas, representing a *path* with 3 segments and 4 *nodes* connecting supplier CSUi to customer CSUj.

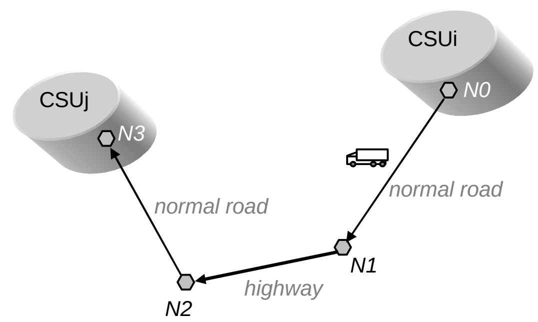


**Fig. 5** Path connecting supplier CSUi to customer CSUj including normal roads and highway

If one assigns a *limit speed* to each *path segment* and a certain *vehicle speed* to each *vehicle*, then the effective speed of transport in that particular *segment* can be calculated as:

*transportSpeed = Min(segmentSpeed, vehicleSpeed)*

Thus, each time the *vehicle* reaches a new *node* leading to a new *segment*, it must recalculate its next speed of transport. As it is easily understandable, the *limit speed* assigned to a *segment* can serve to model not only the legal limit speed of that road but also the usual conditions of traffic flow on it.

In order to model other more specific aspects related with the delivery process, nodes will be of four different types: <u>*normal*</u>, if it is a node where the vehicles just change to a new path segment; <u>*CSU*</u>, when the node refers to a CSU; <u>*transfer*</u>, when the node is used to transfer material from one vehicle to another; and <u>*pause*</u>, when it represents a certain delay in the delivering process. This, of course, can also contribute to the mean speed of delivery observed between CSUs.

## 5. Costs

Once the supply chain is seen as a dynamic system, the costs associated with it must also result from a dynamic process, that is, they will be calculated and affected to the respective CSUs by means of certain event executions in time. Thus, it is important not only to know the amount of a particular cost but also the time when it must be affected to the CSU. This will also allow a continuous calculation of *costs* and *incomes* during the simulation process, for example, important economic indicators for the supply chain manager.

Based on the idea that each process in a CSU must have its costs, and considering as main processes the *purchasing*, the *stocking*, the *manufacturing*, the *delivering* and also the *management*, as depicted in the figure 6, it was decided to specify the costs following this same kind of taxonomy.

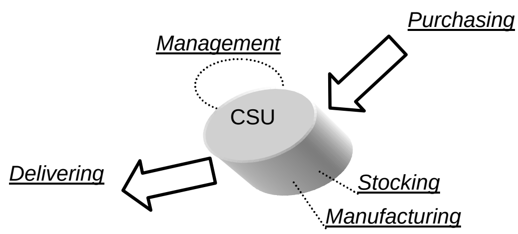


**Fig. 6** Main processes for assigning costs to a CSU

We will talk about *purchasing costs*, *stocking costs*, *manufacturing costs*, *delivering costs* and *management costs*. Each of these costs can be thought as the result of other more specific costs, some of them assumed *fixed* and others *variable*, anyhow, it is important to bear in mind the more the costs are specified the more events one need to add to the model. Here we will only be interested on those costs usually considered more relevant, and each of them handled as a *fixed* and a *variable* component. The *fixed* will be considered the price to pay for "existing", while the *variable* will represent the price to pay for "operating" or "processing".

### 5.1 Purchasing costs

These costs must be affected to the CSU at the end of each *purchasing cycle*, that is, when products (or materials) are received from (and paid to) the supplier. The amount of these costs depends on the <u>*price*</u> previously established for the products by the supplier, as well as on the <u>*administration*</u> involved in the process. This last aspect is modelled as a cost per purchasing cycle, and contains the idea of the "*setup cost*" usually referred in *inventory management* literature. So, the purchasing cost will occur in the end of each *purchase cycle* and its amount will be given by:

*PurchasingCost(t)=*<u>*ProductsPrice(t)*</u> + <u>*administration(t)*</u>

Where administration can refer to invoice prepare, papers, phone-calls, etc., and also to personnel costs. Purchasing costs are considered here only as *variable* costs.

### 5.2 Stocking costs

The process of stocking includes many aspects, and so, many kinds of costs can be assigned to it. However, the most usually considered costs[1] are *operations*, which include receiving, order picking, replenishment, etc.; *administration*, including order processing, managing accounts, personnel, etc.; *occupancy*, which includes rents, services, insurance, depreciation, maintenance; and *inventory*, or *holding* costs, based on the existence of products in stock, usually 1% above the bank base lending rate. The overall stocking costs can then be expressed as:

$$StockingCost = [\underline{operations(t)} + \underline{administration(t)}\ ] + \\ + \underline{occupancy} + \underline{holding\ cost(t)}$$

To turn the simulation process simpler, we will call stock processing cost to the operations and administration costs together, which are considered per unit of material handled. Then, the occupancy cost is based on a fixed cost per unit time (a fixed cost). And finally, the holding cost is based on the price of the money invested on the products in stock.

*Stock processing* costs and *holding* costs will be affected to the CSU at the end of each action of input or output on the stock (variable costs), while o*ccupation* costs will be affected continuously, as the time increases (fixed cost). It is important to notice that the *holding* costs begin when the CSU pays the product to the supplier and will only end when the CSU receives the payment for delivering it to the customer, thus also *in-transit* inventories are considered.

In general, the *holding* cost for the $i^{th}$ product in the stock will exhibit the following dependence on time:

$$HoldingCost(t)i = (Cp)i \times (Np)i \times (HC)i \times (t\text{-}to)$$

Where:

$(Cp)i = i^{th}$ product unit cost.
$(Np)i$ = Quantity of products $i$ in the stock.
$(HC)i$ = holding cost rate per unit time (bank lending rate)
$to$ = Instant of time when the product was purchased
$t$ = present time

There are also costs associated with *stock breaking*[2], each time the demand cannot be satisfied from the stock. These costs will be estimated by the quantity of material that have not been served, thus generating a *stockout*, as well as by the time spent to serve the customer compared with the time the customer accepts to wait for the materials to arrive, leading to a measurement of a "*customer satisfaction index*".

### 5.3 Manufacturing costs

In the present approach the factory is considered to be similar to the warehouse, with the differences that it will have two kinds (*R* and *P*) of products in stock (R for raw materials, P for finish products) and also a *process* named *manufacturing*, which will be responsible for the transformation of *R* products into *P* products. Basically, the manufactory is then seen as a warehouse having a frequent rearrangement of products in its inventory. Such a rearrangement is imposed by the *manufacturing* process.

As the figure 7 suggests, the costs associated with the process of *manufacturing* will mainly be the costs of *transforming R* products into *P* products (variable cost), the costs of labour (assumed as a fixed cost), and the costs of space occupancy (fixed cost) for the production zone. The costs associated with *stocking*

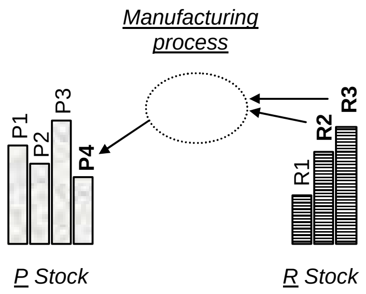


**Fig. 7** Equivalent of a manufacturing process, in this case products *R2* and *R3* will give product *P4*.

will be the same referred in the previous section. The *transforming* costs must be specified for each product *P* in the factory, and given per unit of product. Of course, these costs must be affected to the CSU at the end of each *production cycle*.

Then, after a certain period of time *t*, the contribution of the *manufacturing* process for the overall *variable costs* of the CSU will be given by:

$$ManufacturingCost(t) = \sum [\underline{transforming(t)}]_i$$

Where *i* referes to the *ith* product manufactured in that same period of time.

Finally, the *occupancy* costs related with the factory's zone, as well as the *labour* costs, will contribute to the global *fixed costs* of the CSU.

### 5.4 Delivering costs

Delivering costs are here considered as the result of two main contributions: occupancy, related with space reserved for the fleet, garages, or even rents, if the fleet doesn't belong to the CSU; and transport, which include the costs associated to drivers, vehicle consume of fuel and oils, paid roads, meals, delays, handling the materials, and so on.

Similarly to what was considered in the *StockingCost*, the occupancy cost is seen as a fixed cost, and given per unit time. The transport costs, however, will be computed during the simulation process each time a *vehicle* reaches a new *node* in the transport path network, and assigned to the respective CSU when the material reaches its destiny. Thus,

$$DeliveryCost = \underline{occupancy} + \underline{transport(t)}$$

The transport costs include the following main aspects: *fuel*, *lubricants*, *maintenance* and *roads* as costs depending on the distance travelled (ds); *drivers*, depending on the time travelled (dt); and *meals* and *delays*, as constant costs. As an example, if a vehicle is going from *node A* to *node B* with a speed *v*, the following *transport* costs will be added to its CSU when reached the *node B*:

$$Fuel(ds) = (VehicleFuelConsume/PricePerLitre)*ds$$
$$Roads(ds) = (PriceOfRoadPerKilometre)*ds$$
$$Driver(dt) = (DriverPricePerUnitTime)*(ds/v)$$

Where *lubricants* and *maintenance* can be considered included in the *fuel's* price. Notice that when the node corresponds to a node of resting or meal, also the constant costs of resting or meal must be added. Also notice that hiring the services of an external fleet can be modelled as keeping the cost of occupancy null.

### 5.5 Management costs

The *Management* costs, related with the costs of managers, analysts, secretaries, strategists, marketing, etc., will be considered here as *fixed* costs, and, as a first approach, they must be included in the fixed costs of the main resource of the CSU, that is, the inventory. These costs are also affected to the CSU as a continuously growing cost.

### 5.6 Total and global costs calculation

Each of the previous *variable costs* are recorded during the simulation as *instantaneous* values, thus, the calculation of their *totals* will automatically result from the simply sumation of those values along the time domain. For instance, considering the output transport costs the function $g(t_i)$, which would have the form of a data output record from the simulation, the *total variable costs of transport* would simply be given by:

$$total = \sum_i g(t_i)$$

This is a general method used in this modelling approach to record the behaviour of the interesting variables during the simulation run, which simplifies future calculations. For example, it will turn the calculation of *global costs* extremely simple, not only in a particular CSU but even in the entire chain network.

## 6. Information and the flow of money

Other things flowing in the chain are *information* and *money*, which in the present approach we consider associated with instantaneous operations. At the moment, the *information* will mainly be related with the communications between CSUs during material ordering, but we expect to include more about that in the near future, mainly the transference of the clients demand to the CSU's suppliers, in order to transfer the demand upstream on the chain, a procedure claimed to improve the partner's flexibility.

But let's now concentrate on the *money* flow, related with the payment to the supplier in the moment the material reaches its destiny. We make the following assumption: money always flow in the opposite direction of the material flow, that is, each time one receives materials one has to pay back its price to the supplier. It is based on this process of exchange the chain will maintain its activity along the time. The payment is here considered to be instantaneous.

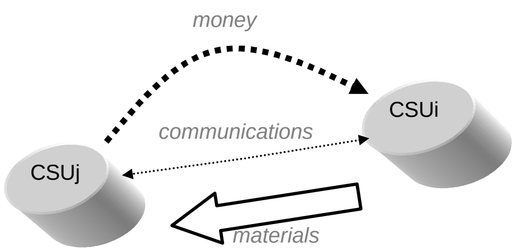


**Fig. 8** Exchanging process between supplier CSUi and customer CSUj

The introduction of this economic aspect will give the analyst the possibility of studying the evolution of the chain parameters along the time not only based on technical performances but also taking into account economical aspects, as in fact it happens in reality.

Money flow will be triggered each time a customer receives material from a supplier. As the chain continues to work, such flow will spread to all the elements in the network, then allowing the instantaneous calculation of the *variable costs, incomes, total costs, etc.*, as well as certain important economical index, as the *cash flow*, for instance.

## 7. Modelling the general CSU activity

As we have seen, in each CSU some processes are running and interfacing with each other to create the complex activity of the unit. Those processes are the *purchasing*, the *stocking*, the *production*, the *delivery* and the *management*. Except the *management*, which is here considered instantaneous and coincident with any events in the CSU, each of the other processes contribute to the overall CSU's state with a certain number of states (we call *live states* those states which duration can previously be known or computed, and *dead states* those states where this cannot be done, as in waiting states and queues, for instance)[3]. The collection of such states, and the possible connections between them, will form the *state diagram* of the CSU, the real basis for the model. Therefore, first we have specified the *state diagram* of the CSU, and then converted it into a sequence of events which finally have been translated to a programming language code, in our case the C++.

Notice that, while building the supply chain network in the simulator, the user will no longer need to think on those internal states of the CSU, as they become endogenous to the CSU object, turning the supply chain representation more likely a game of objects connected between each other by paths of information and material flow. Thus, at the user's point of view, the paradigm used in the simulation is a *real object paradigm* and not any of the usual basic paradigms described in simulation literature like Petri-nets, activities, events, processes, 3phase, etc.

### 7.1 The purchasing process

This process is the process of ordering material to suppliers, and starts in each of the conditions: (1) The present stock control policy determines it is time to reorder. (2) There is an order from a client that cannot be fulfilled direct from stock and, in the case of accepting *backorders*, new material can be ordered.

After creating and preparing the new order with the material requirements, each of these "procedures" will then trigger the start of the purchasing process, which in fact reduces to two "events": (1) The sending off the new order to the respective supplier, we named *e_order()*. (2) The receiving of the material arrived, we named *e_arrive()*. Between theses events the process will be in a *dead state*, waiting the material to arrive from the supplier.

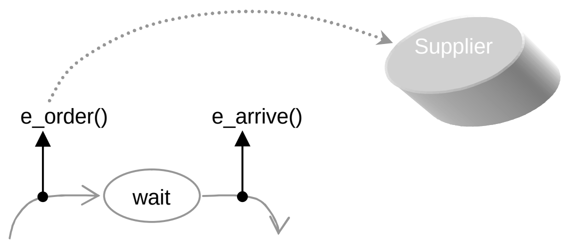


**Fig. 9** The basic purchase process.

Notice that *lead times* are initially unknown, as they result from other dynamics internal to the CSU supplier and on the transport speed and availability, for example. Also notice *e_arrive()* can be thought as the beginning of a subsequent *live state* which in fact represents the UNLOAD activity. This will let us later substitute the event *e_arrive()* by the event *e_startUnload()*.

### 7.2 The stocking process

We considered the *stocking process* the gathering of two distinct processes: the *input process* and the *output process*. As their names state, the former is responsible for inputting material to the stock, and the later for the output of material from the stock. Figure 10 gives an idea of the events and activities involved in the *output process*:

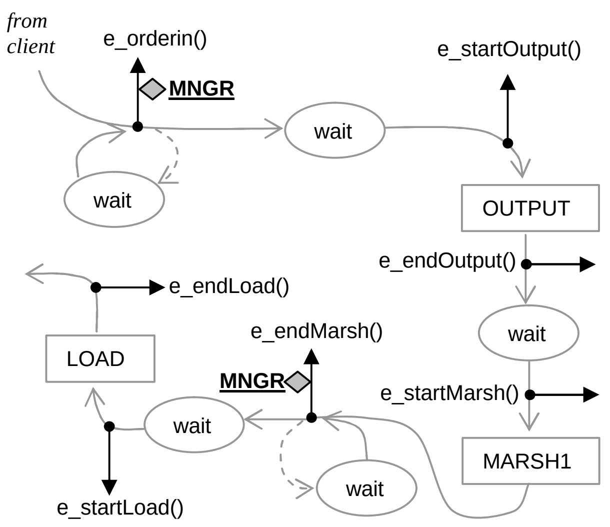


**Fig. 10** State diagram of the stocking output process.

Basically, an order-for-output from a client enters the CSU by means of an *e_orderin()* event. This event will then ask permission to an upper-level "*manager*" for the satisfaction of such an order. The "*manager*" will decide if the order will be immediately served, rejected as *stockout*, or made to wait to be satisfied later when new material will arrive from the supplier. As long as the order can be served, the process enters in the phase of outputting the material from the stock. Then the material will be prepared and packed at the MARSH1 activity, and the order becomes ready to be sent to the client. Anyhow, the "*manager*" called by the *e_endMarsh()* event will decide whether or not the order wait for later LOAD and transportation, keeping it in a different waiting place depending on such a decision. The event *e_endLoad()* will trigger the *delivering process*.

The *input process* is basically the inverse of this process. However, in the present approach the *input process* is considered reduced to the activity of UNLOAD, which is due when new material arrives in a vehicle from a supplier. This is the same as considering the material will be available in the stock precisely at the start of the UNLOAD, which great simplifies the modelling. In fact, as not-yet-fulfilled orders will have to wait in the queue before OUTPUT activity, this approach is expected not to lead to significant discrepancies in the results, as it is as if the *input process* would, in the worst case, run in parallel with the *output process* and then, in average the material will already be in stock when it must be taken out. This consideration was mainly used to simplify instantaneous holding costs calculation during the simulation process.

### 7.3 The delivering process

This process is responsible for carrying the material to the clients. As it was referred earlier in this paper, this can be done by many different ways, using from normal roads to airlines, and thus the efficiency of this process will be great dependent on the kind of transport it assumes. Although the delivery process is conceptually very simple, as it is presented in figure 11, it can turn much more complex in certain cases, for example, when using paths of *transfer* vehicles between two nodes or when the delivery paths are complex. Anyhow, the vehicle entities will be responsible themselves to handle all the material while they move along the network, what will make them practically transparent to the delivery process as it is defined in the present figure.

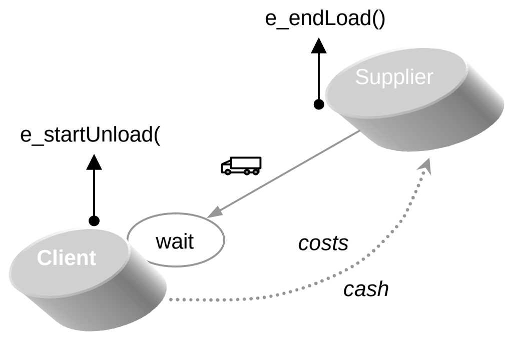


**Fig. 11** The basic delivering process.

Thus, one considers that this process begins with the event *e_startDelivery()*, which is equivalent to *e_endLoad()*, and will end in the moment the vehicle will be received by the CSU client at the event *e_startUnload()*. In the case of more than one vehicle on delivering to the same client, probably there will be the need to wait for a free *inputBay*, as figure suggests. With this model only during or after the simulation one will be able to estimate the *lead times* of the system. Unlike certain Supply Chain Simulators, here *lead times* become outputs from the simulation, and not inputs. Nevertheless, the time spent on the return of the vehicle to its home is estimated, considered to be 75% of the time consumed to reach the client. At the end of this process costs and other parameters are computed, and the respective *cash* made to flow to the right suppliers.

### 7.4 The manufacturing process

The *manufacturing process* is modelled here assuming no product mixing and only one line of production for each product manufactured. This, of course, can be made more complex in future, but at the moment it will be treated in this simplified form, as our main concern is to focus the attention in the overall supply chain behaviour and not particularly in production. In a wide range of real cases, however, this model can be used without affecting significantly the results. The state diagram of such model is presented in the next figure.

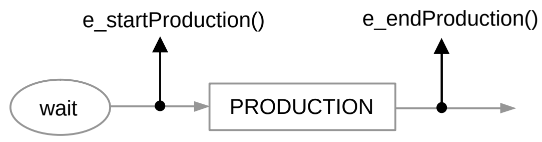


**Fig. 12** The basic manufacturing process.

There is a waiting state (queue) for the orders waiting to enter the production, and the events *e_startProduction()* and *e_endProduction()* signalling the start and the end of the PRODUCTION activity. This model also uses the classical concepts of *production rate*, which establishes the maximum frequency the orders can be made to enter the PRODUCTION activity, and the *raw cycle time*, what defines the time spent by each lot in that same activity.

The start of the *manufacturing process* will be triggered or by the <u>*stock level*</u> of the product to be produced, or using a <u>*cycle*</u> as in the case of continuous production. This will be established by the user. At the proper time, the necessary products and the respective amounts are removed from the stock (using the *output process*) so that the new product can be produced by the *manufacturing process*. At the end, the new product will be added to the stock of the CSU and the related costs computed.

## 8. About the operational policies in the CSU

The overall activity of the CSU is also dependent on the operating policies adopted, being the most decisive of them the *inventory policy* (how to order the materials), the *production policy* (how to produce), and the *delivery policy* (how to bring the materials to the customers). In this section we briefly present some considerations about the policies implemented in the scope of this modelling approach. To handle such tasks each CSU C++ object includes a *CSUManager()* method to concentrate the code associated with these policies.

<u>The *delivery policy*</u>, for instance, belonging to the FLEET-MANAGER section of the *CSUManager()*, is in this first version very simple: each time the material must be carried to the customer, a vehicle, if any available and free, is loaded with the material and sent to the customer. Otherwise, it will wait. There is not yet *multi-drop* delivery implemented, although different products can integrate the same order.

<u>Concerning the *production policy*</u>, it is given to the user the following three options of managing: ON-DEMAND, if the production is only to start when there is an order from the client which cannot be satisfied directly from the actual stock. BY-LEVEL, if the production is triggered by the level of the stock. BY-CYCLE, when the production is to be continuous and restarted cycle by cycle.

<u>Finally, in the *inventory policies*</u> one can already use a wider range of management options, which go from the simpler (r, Q) and (r, S) models till the notions of *Safety Stock*, KANBAN, Economical Order Quantity (EOQ), and a more general (r(t), Q(t)) model which is expected to try to adjust *r* and *Q* to the demand pattern along the time. In fact, the actual main core of the CSU management is this set of policies, which can be used by the analyst to test different management strategies and other concepts within the model. More about this issue will be presented in a paper to come.

## 9. RESULTS

The main results of this approach is a software application focused on *Supply Chain Simulation* with which is possible to compare different scenarios in terms of some common Supply Chain Metrics. With such a simulator one can also test operational policies in response to different patterns of demand, in order to have an idea on how fast the chain is able to adapt to demand changes, thus getting an indirect and qualitative measure of its flexibility, as well as of the parameters that can interfere with such flexibility. In fact, this approach also includes a first trial to measure and quantify FLEXIBILITY, or AGILITY, although we only expect to refer to such a subject in a future presentation.

At this stage, we will finish by presenting a simulation of a relatively simple model which is usually used by the *University of Cranfield* (UK) as a didactic supply chain management exercise[4], considering only one product in the chain and all the delivery times set to be one cycle.

Figure 13 shows the network structure used on this exercise, named "*Cranfield Blocks Game*" (Richard Saw 2002). Usually, this game is played with seven groups of students, each group being responsible for the management of a single facility. The customers demand (*Cj*) is random generated, and the supplier (up on the figure) is considered an infinite source of materials. Thus, the groups are only endorsed to manage from the *Depot1* to the *Factory*. No backorders are considered, and each facility has to

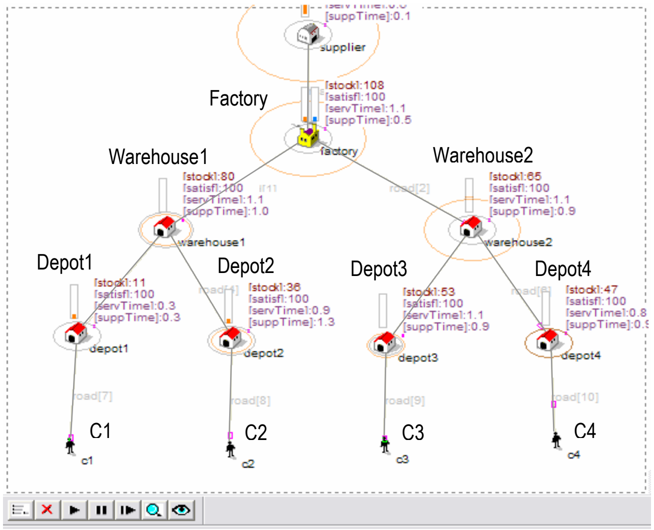


**Fig. 13** Cranfield Blocks Game, being simulated.

adjust its reorder quantity to a multiple of a certain *Base Quantity* (BQ) which increases as the facility approaches the *Factory*. All the activity in the chain begin with the customers demand (*Cj*), and the goal of each facility manager is to <u>fulfil demand keeping the *stock* as low as possible without incur in *stockouts*</u>. The average level of costumers demand increases from left to right in the chain, meaning *C1 < C2 < C3 < C4*.

As merely didactic results we present now some output data achieved with the simulation of this case, using in each facility the (r, Q) inventory control model.

The first chart (Fig. 14) shows in different colours the DEPOT3 *local* and *in-motion* <u>stock levels</u> along the time, as well as the <u>demand</u>, the quantity of <u>material arrived</u> from the supplier and also the quantities of the <u>stockouts</u>.

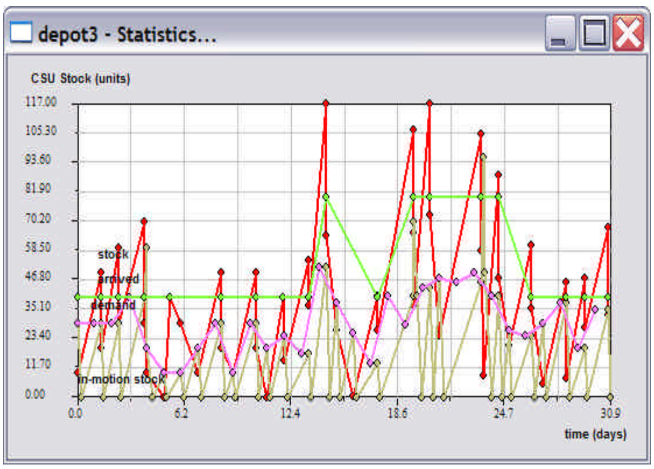


**Fig. 14** Depot3 stock levels versus time.

In the next figure (Fig. 15) is plotted how the WAREHOUSE2 *variable costs* were running with the time. It shoes that was observed a certain stability in the purchasing costs, in the delivery costs and in the holding costs, comparing with higher amplitude variations observed in the stocking costs due to the input and output of materials from the stock. However, these results have been obtained considering default values in the stocking process, what gives them no special significance.

*Accumulated costs* are also computed during the simulation run, letting the user have an idea of the total amounts involved in the CSU activity during the simulated period of time, and can be observed in another sort of chart, not presented here.

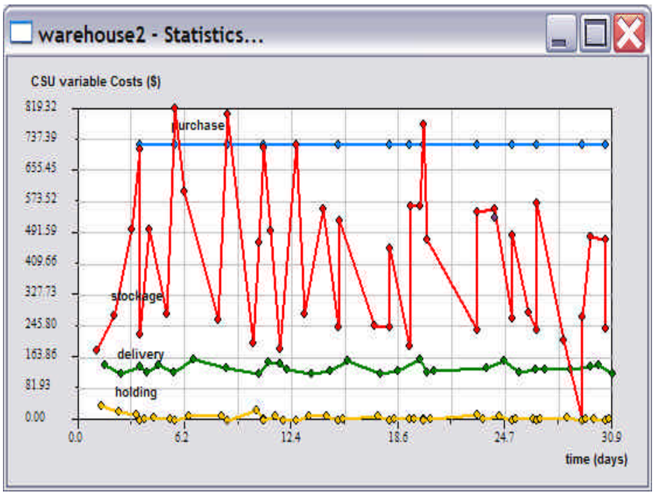


**Fig. 15** Warehouse2 variable costs versus time.

The next figure (Fig. 16) relates with WAREHOUSE1 and shows the variations of the supplier's lead time compared with the average time to serve clients. It also shows the delivery time, here considered to be equivalent to the transport time. Based on this information the analyst can better estimate how much the behaviour of such times can affect the performance of the CSU, as well as to project more reliable inventory policies that can better adapt to its suppliers response times. Based on this data the analyst also can understand, for instance, why a certain customer is not being satisfied, whether it is due to its delivery policy or due to its suppliers lead time pattern.

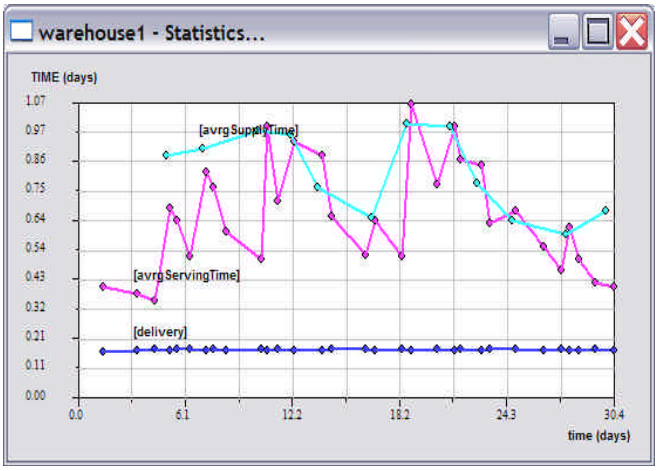


**Fig. 16** Some Warehouse1 times versus time.

Finally, figure 17 shows some measures used as Supply Chain Metrics, in this case associated with the WAREHOUSE1 performance computed after 5 simulation runs. On this char is represented the estimated average values and also the variability of measures like TotalCosts, Incomes, Turnover, ServiceLevel, StockoutRatio, etc., thus giving the user the final ability to evaluate different policies implemented in the CSUs, as well as the capability to compare the performances of the different partners in the chain.

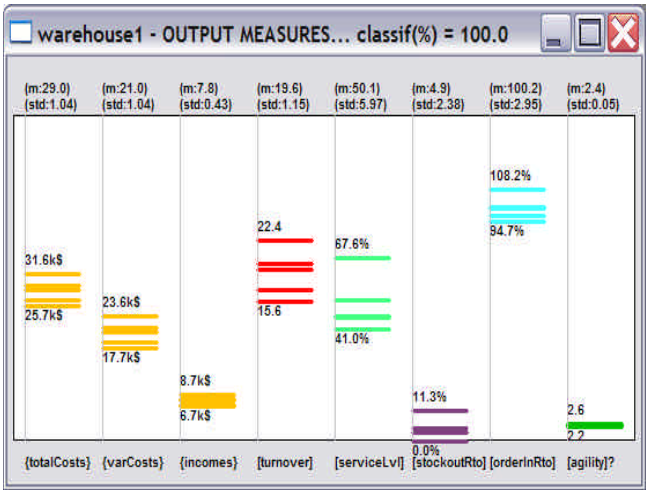


**Fig. 17** Warehouse1 output measures after 5 runs.

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[2] José Fernando Gonçalves, *"Gestão de Aprovisionamentos"*, Edição revista, Publindústria, 1999

[3] António E. S. Carvalho Brito, J. Manuel Feliz Teixeira, *"Simulação por Computador"*, Editora Publindústria, Junho 2001

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# Visual C++ software for warehouse simulation (an overview)

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**ABSTRACT**

This paper presents an overview of a *visual and interactive warehouse simulator* developed with *Visual C++* for *Windows95/NT* operating system. This simulator have been designed under an *object oriented programming approach* and looks to the warehouse by an hierarchic decision level point of view, which allows an interesting separation of the responsibilities on the system. It is a modular approach where each entity is responsible for its own integrity and functionality, and where the decision rules are separated on three fundamental levels[i]: *element level*, *control level* and *management level*. Nevertheless, the main interest of this paper is not to introduce any kind of code statements of the simulator, but instead to present the reader the structure of the more relevant elements and the way they were modelled. At the same time it will be shown some of the user interface facilities and also some references to studies made using this warehouse simulator.

## 1. Introduction

Warehouse automated systems are nowadays fundamental equipment to ensure the modernisation of production and distribution centres, to improve their flexibility and also to rise their processing capabilities in order to answer with more efficiency to the actual market demands.

The importance of simulation modelling in this field of industry is from all recognised. Anyhow, commercial software modellers appear to be or too simple to permit a reasonable modelling of the real system or too complex to consent to build it in a proper time, and for these two main reasons only few Portuguese enterprises stand making some efforts in the field of simulation[ii].

Nevertheless, with the evolution of programming languages towards *Object Oriented Paradigm*, given its decrease of price and its improving flexibility and also due to the excellent tools to build the user interface, simulation is becoming practicable, even in those cases implying specific development solutions. This simulator is in fact a case of a modeller directed for a particular area of interest, the automated warehouse systems.

## 2. Objectives

This *interactive warehouse simulator* was developed due to two main reasons: first, the tradition of knowledge in this laboratory on such matters, deep connected to the early work of António E. S. Carvalho Brito[iii]. Second, the obvious interest showed by EFACEC Portuguese company on our project of developing such a simulator.

Therefore, the main objective of this work was to project and develop a *visual interactive warehouse simulator* that could be used by that Portuguese company on its warehouse studies and building. The work have been started in 1996 and lasted for two years on conception and implementation of the elements and decision rules widely used on that company. Nevertheless, the final conception has been completely new, mainly due to the introduction of the *three levels decision logic* mentioned earlier.

The simulator flexibility and the possibility of configuring each element on the warehouse in a simple manner, as well as the capacity of simulating practical warehouse systems, were the main intents on the beginning of the project. Such demands implied a deep study of each of the elements to simulate, a carefully choice on the program structure and the development and implementation of certain algorithms for material moving inside the warehouse.

This leaded to a final *b-version* that is being used by that company since 1998 on its most important warehouse projects, two of them related with a study of a warehouse to Brasil[iv] and a study for building a warehouse in Iran[v].

## 3. The simulator's base application

The base application, developed under Microsoft Visual C++, is a standard single document *Windows95/NT* application on which some useful tools were added. Such tools, however, were mainly separated on "drawing tools", by which the user is expected to draw the layout on the application's view, and "simulation tools" which are related with the creation and configuration of the warehouse elements, such as *conveyors*, *racking vehicles*, *transfers*, *transfer tables*, etc…

Next figure (fig.1) shows the main view of the simulator application.

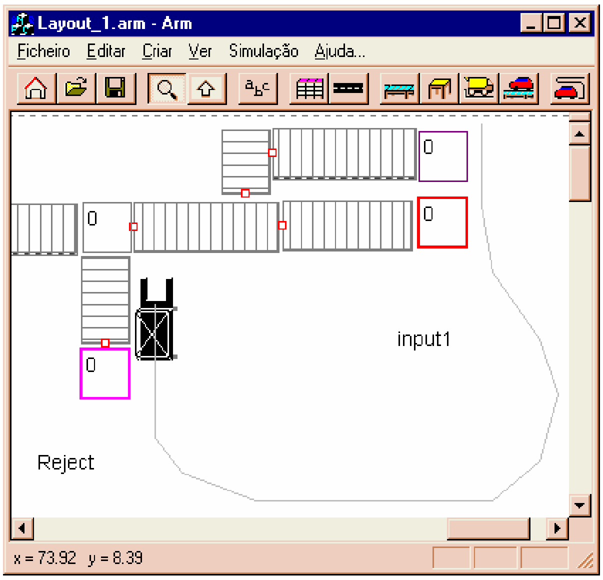



Fig.1

In the "<u>drawing tools</u>" were considered the following facilities:

- Interactive polyline draw with the mouse.
- Runtime creation of drawing objects.
- Scale representation in meters.
- Text inclusion in the interactive view.
- Facility of selection objects with the mouse.
- Facility of moving objects in the screen with the mouse.
- Facility of deleting and duplicating objects with the mouse.
- Facility of window zoom.
- Filter for element intersection.
- Continuous display of real coordinates.
- Floating menu to access the properties of each object.

These background tools let the user actions be very simple when drawing the scaled warehouse layout on the simulator's interactive view.

In the "<u>simulation tools</u>" there were included the creation and configuration of the warehouse layout elements (conveyors, racking vehicles, etc.), the definition of the paths where vehicles are due to move during the simulation run, and the functions to analyse the overall layout's data consistence. These tools also include some items to manage the simulation process.

Most of the "<u>Simulation tools</u>" can be accessed both from the application's menu and from the top *toolbar* shown in the Figure 1.

## 4. Creating the warehouse elements

After creating a new simulator document on this application, where the user have previously defined its rectangular dimensions (in meters), there will be presented to the user an empty view where he is expected to draw the new layout with the help of the application's tools. In this way, he will be responsible for the method or sequence in which he will draw the layout. As in the most cases there is no need to follow a specific order to create the objects, the user can do this task the way he prefers. In fact, he can first create the conveyors and then the racking systems, and then the racking vehicles, or to choose any other method of his own sympathy.

During this process the layout is being represented on the simulator's view, staying all the elements accessible to the user to be changed, deleted or moved within the layout's predefined space. Each warehouse element has associated a property box on which its characteristics can be entered or modified later.

### 4.1 Racking storage elements

*Racking elements* for palette storage can easily be created with the aid of one of the *toolbar* buttons and subsequent use of the mouse to define the racking dimensions.

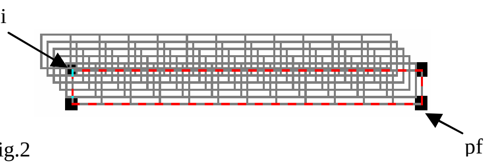
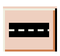



Fig.2

These dimensions are established by choosing the points <u>pi</u> and <u>pf</u> of the racking as represented in Figure 2 by means of a simple mouse action, which define the <u>initial</u> and <u>final</u> points of the racking. In this Figure it is also represented the vertical dimension, what lets the user easily visualise the racking overall capacity of storage. Accessing the property box of this kind of elements it is possible to modify the default parameters for racking storage creation. The overall *racking storage system* of the warehouse is then the group of all the *racking elements* created by the user.

### 4.2 Vehicle path network



Vehicle *paths* are polylines defined by the user along which *racking vehicles* are due to move while handling the jobs during the simulation run. As in the previous case, *paths* are easily created by interactive use of the mouse, what speed up de process of entering the layout's data into the simulator's window. The user draws each single *path* on simulator's view, and the group of all the *paths* defines what we called the *vehicle path network*. *Paths* are also the elements through which the simulator associates *racking vehicles* to racking storage elements, and other vehicles to tables and input or output points.

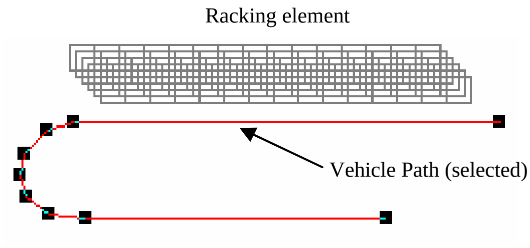



Fig.3

The association of *paths* to *racking elements* is an automatic process that runs before the simulation start, and the method of association is related with the distance from the *path* to the *racking* (fig.3). The same is true for transfer tables and input or output points.

### 4.3 Conveyors

*Conveyors* are the dynamic elements used to transport palettes through the warehouse and usually are used to connect the peripheral input and output points to the storage zones. As in the previous cases, *conveyors* are created interactively by the definition of only two points: the initial point (pi) and the final point (pf). The default direction of movement is from pi to pf, so defined by the user during the creation of the element.

Next figure shows a *conveyor* prepared to transport palettes from left to right. The small square in one of the conveyor's endpoints defines the default conveyor end, and then its default direction of transport.

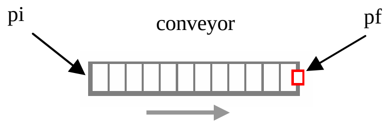



Fig.4

Other parameters of the *conveyor*, like its width or its speed or the unload time, are due to be modified on the element's property box accessed by a simple mouse DOUBLE-CLICK over the element.

Being a dynamic element, the *conveyor* is related with certain events that define its behaviour, which lead to the implementation of the related event handlers on this *class* of objects. This leaded to the possibility of observing the movement of the palettes on top of the conveyor during the simulation run.

### 4.4 Transfer tables

In general, *transfer tables* are the interface elements to be used between different kind of material handlers and in the case of bifurcation of the paths where the material flows. Material handlers are considered in this simulator to be *conveyors* and *vehicles*, and then, to ensure the transfer of palettes between them one must use *transfer table* elements. In this perspective, the *transfer table* is seen as a cell for intermediate storage of palettes, and so the warehouse a site of a certain number of cells connected by *handler elements*. In this software version *transfer tables* are also considered static objects (with no events associated) which activity depends directly on the *dynamic elements* activity (*conveyors* and *vehicles*). Nevertheless, there is one kind of tables, named *Inspection Table*, that is considered closer to a dynamic element due to its active role on the simulation process. In fact, *Inspection Tables* are used to inspect the material and then to decide for its rejection or not.

*Transfer tables* are represented as rectangles whose dimensions are first specified by the user in the element's property box.

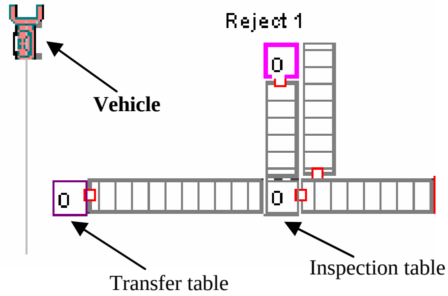



Fig.5

Figure 5 shows the two kinds of tables within a *conveyor* network interfacing with a distribution *vehicle*. It is important to notice that each *table* is previously configured to support certain directions for material flow (this is also defined by the user).

### 4.5 Input and Output points

*Input and Output points* are the elements by which the warehouse interfaces with the outside world. The material enters the warehouse through the *Input points* and leaves it through the *Output points*. Mainly these points are derived by the previous *table* concept, however they are active elements on the system due to its capacity of generating new events during the simulation process. Each of them is previous configured by the user by accessing its property box, where one can establish the palettes input or output rate as well as other parameters related with its physical dimensions and material flow distribution.

Although these elements were first created to play the role of inputting and outputting material, later they have been generalised to include two new cases: the *picking point* and the *rejection point*. The *picking point* is a special point where the material demands are generated manually by an operator, while the *rejection point* is a point to where the material will be directed in the case of rejection by an *Inspection Table*. Each of these special points can be seen as a mixture of input and output points, as the material can be redirected to the system after a certain time of processing inside that point.

As in the case of *Transfer tables*, each of the *points* considered here is represented on the simulator view as a rectangle which dimensions can be defined by the user accessing the correspondent property box.

Next figure (fig.6) shows a part of a layout that includes these kind of points.

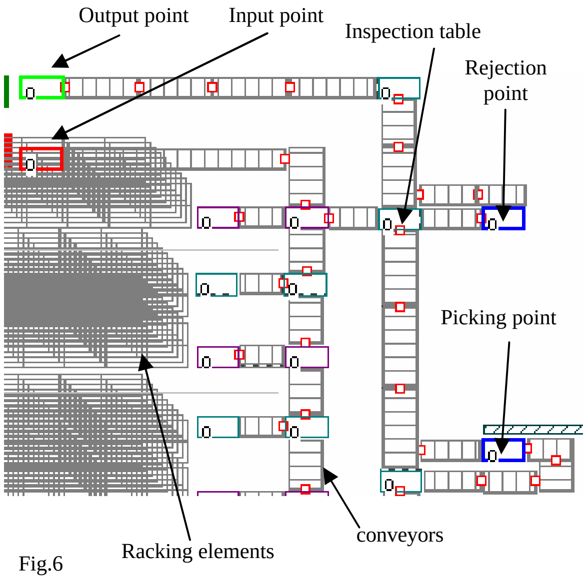



Fig.6

## 4.6 Vehicles

*Vehicles* are the dynamic elements that use *paths* to move through de warehouse while handling certain jobs. As in practical warehouse systems there is some different kinds of vehicles, in this simulator it was included five different types that were considered more relevant by the company EFACEC to ensure that this simulator could be able to model a wide range of layouts. All of these *vehicles* play the role of *material handlers*, although some are more adapted to certain jobs than others. For instance, there are *vehicles* with the capacity of accessing *racking elements*, while others only are able to move the material between *tables* or input/output *points*. Next figure shows the five types of *vehicles* included in this simulation software.

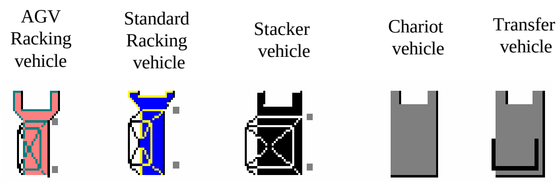



Fig.7

**AGV Racking vehicles** are *Automated Guided Vehicles* (AGV) with the ability to access *racking elements*, meaning that they are mainly used inside the storage zones of the warehouse.

**Standard Racking vehicles** are *vehicles* that move over static predefined aisles and also have the ability to access *racking elements*, also used inside warehouse storage zones.

**Stacker vehicles** are *vehicles* that usually have a relative freedom of movements, guided by an operator, and with the ability to execute stacking actions between different parts of the warehouse, mainly between *tables* and input/output *points*. In this simulator this kind of *vehicles* is not considered to be able to access *racking elements*.

**Chariot vehicles** are *vehicles* that usually move over static inline predefined aisles and are mainly used as palette distribution elements, so acting between *tables* and input/output *points*.

**Transfer vehicles** are *vehicles* that move over static predefined aisles which main purpose is to transfer other vehicles from one place to another. These *vehicles* are usually associated with *Standard Raking vehicles* when it is necessary to transport these elements to different aisles. However, *Transfer vehicles* are also due to handle palettes in certain particular cases.

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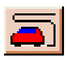
The user creates each of these *vehicles* with a simple mouse action choosing its type from a <u>vehicle list</u> included in the simulator. Once created the *vehicle* it is possible to configure its parameters using its property box, in order to adapt them to the desired values if different from the default values.

To each *vehicle* must be associated a group of *path elements* that will define the area within the *vehicle* can move later during the simulation run. In this way, it is possible to define different areas on the warehouse that will be served by different *vehicles*.

In the particular case of the *Transfer vehicle* the user needs also to associate it to the *Racking vehicles* that it will be responsible for.

## 4.7 Vehicle paths



*Vehicles* need that the user associates them to a certain group of *path elements* in order to define their area of action within the warehouse. Therefore, for each *vehicle* the user must choose and select with the mouse a certain number of consecutive *elementary paths* from the overall *path network* previously created on the warehouse. Once this is done for all the *vehicles* the simulator can be considered prepared to start to simulate the movement of those *vehicles* along those *paths*. Any *vehicle* with no associated *path* will be considered <u>inactive,</u> remaining stopped during the simulation process.

## 5. An example of usage

This simulator was conceived to help the user creating a wide range of warehouse models without the need of programming new code. This facility arises from the fact that this simulator already includes in its <u>simulation tools</u> the most important elements used on common warehouses, through which the user can represent a wide range of layouts. Also, the inclusion of *Computer Aid Design* (CAD) <u>drawing tools</u> lets the user quickly represent and configure such elements. The functions that analyse the overall layout's data consistence are another important mechanism to speed up the modelling process.

In this section we present an example of a practical layout modelled with this simulator where there were included most of the elements presented earlier on this paper. The top view of this layout is shown in the figure 8 in a military perspective, where one can see the real dimensions of the warehouse, the racking storage area, the distribution conveyor network and other kind of elements.

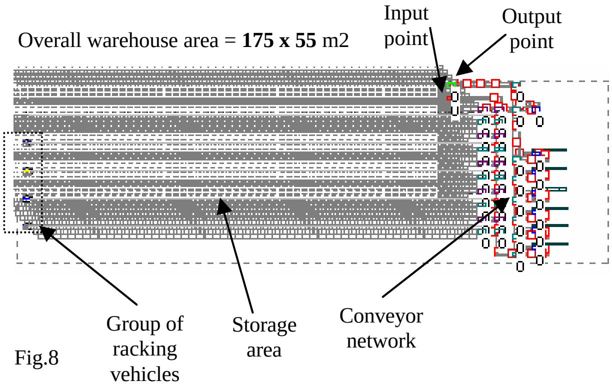



Fig.8

This layout uses 5 *racking vehicles* working each on an independent *raking path* and serving the entire storage zone. The input and output *points* are the interface points with an external production zone, and the material flows in the conveyor zone passing through 6 *picking points*. The storage zone is a group of 10 double deep *racking elements* distributed by the 5 different *raking paths* and has an overall storage capacity of 11600 palettes.

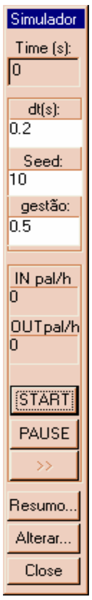



Fig.9

After the layout's configuration, the simulator fills the racking storage elements with a random distribution of palettes and then the simulation is ready to start. The start command consists of a simple pushing of one of the simulation control buttons (START) of the simulation control window that appears meanwhile (fig.9).

In this window the user is able to configure some static parameters of the simulation process, like the time interval of sampling for visual movement effects [*dt(s)*], the seed for random numbers generation [*seed*], and a management index [*gestão*] related with the method of choosing the position of the palettes within the warehouse storage.

This window will also keep a continuous display of the simulation time [*Time(s)*] as well as the value of the actual input and output palette rates [*IN pal/h*] and [*Out pal/h*]. The other buttons are used to manage the simulation run and to let the user observe the evolution of the simulation output data [*resumo*].

As this is an example related with a practical layout, all the elements have been configured according to the client requirements, what means that each value imposed on each element parameters corresponds to an expected value for real warehouse systems.

Next figure shows with more detail two *racking paths* and the correspondent *racking vehicles* during the simulation run.

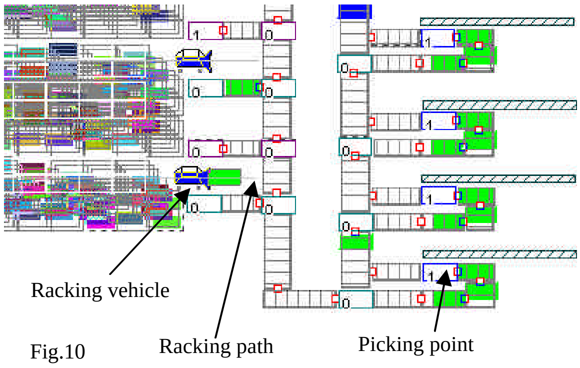



Fig.10

Each *racking vehicle* was configured to have an average speed of 3 m/s and load and unload times of 12 seconds. In this figure are also visible a part of the *conveyor* network, some *transfer tables* and 4 *picking points* where human operators handle the material. Each of these *picking points* was configured with a buffer of 4 palettes and an average working time of 4.5 minutes. The action time of *the transfer tables* was established to be 3 seconds and the mean speed of each *conveyor* 0.2 m/s. The coloured rectangle elements represent the palettes on the layout.

Figure 11 represents a zoom view of the input and output zones connected to the production zone. Here one can see with more detail an *inspection table* and a rejection machine modelled as a *rejection point*.

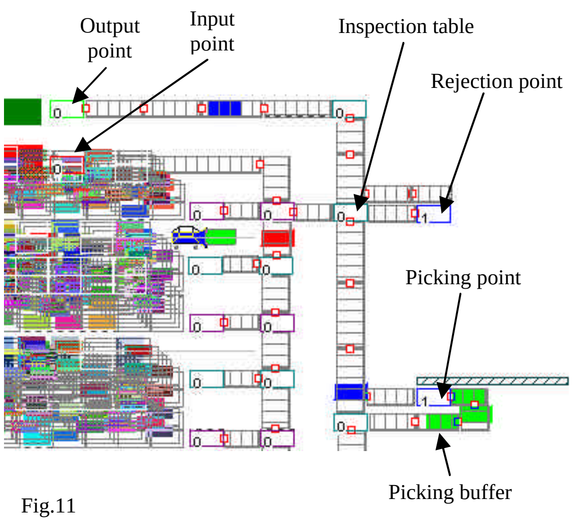



Fig.11

In accordance with the client demands the warehouse overall input rate was established to be 35.6 pal/hour coming from the production zone and a direct output demand of 0.8 pal/hour in the *output point*. The overall *picking points* were defined to ensure a 60 pal/hour processing rate, half of which was directed to the *output point* after passing by the *inspection table*, and the remaining redirected to the warehouse storage.

Although the time spent on modelling this layout has represented two days of work, the main difficulties were related with the element representation on the simulator's view and the configuration of those elements, therefore depending the speed of modelling on the layout's complexity. Nevertheless, after finishing that task it is easy and fast to simulate the warehouse behaviour, and in this case it could be observed that simulation time was 30 times faster than the real time. This performance was achieved even with the simulator running in active representation mode (letting the user observe the movements of the objects on the computer screen), what means that higher speeds could be reached if only using background simulation.

Some of the results obtained with this simulation are presented in the figure 12, where it is plotted the amount of palettes *inputted* to the warehouse storage zone and the overall *output* back to the production zone along the 25 hours of simulation time versus the observed processing time.

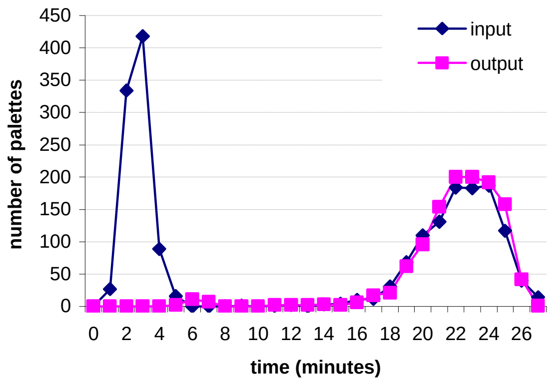



Fig.12

This graph shows a first spike for a large number of palettes with a processing time around 3 seconds, related with the paletes that directly enter in the system through the *input point* coming from the production zone. The second burst with a mean time processing near 23 minutes is due to the pallets redirected to the storage by the group of the six *picking points*. The direct *input rate* observed was 35.6 pal/hour.

What concerns the *output* process, the main contribution is due to those palettes coming from the group of the *picking points* in direction to the production zone (*output point*). The direct output demands were just 0.8 pal/hour, while the overall *output rate* observed was 47.4 pal/hour.

These results were obtained after 24.9 hours of simulation time in which 886 palettes have entered directly to the warehouse storage and 1180 palettes were moving out from the warehouse to the production area. The remaining palettes stayed circulating between the group of *picking points* and the warehouse storage zone. In these processes it have been observed a time occupation of each *racking vehicle* of about 60%.

## 6. **Conclusions**

After using this simulator for modelling some practical layouts, each of them proposed by the company EFACEC with industrial intents, one concludes that in fact this simulator allows a fast development of the model comparing with other multipurpose simulation software packages. This fact is mainly due to the inclusion of basic warehouse elements on this simulator which the user can access and configure in a very efficient way. Those elements, like *conveyors*, *racking vehicles*, *tables*, etc., are independently modelled and accessible to the user with a simple mouse CLICK. Thus, the representation of the layout is reduced to the creation of such elements followed by its positioning on the simulator's view. This method of building the model can therefore be compared with a game where one has to represent the warehouse as closer as possible to the real warehouse. Of course the time consumed on this process depends on the layout's complexity as well as on the precision with which the user wants to build the model. Nevertheless, the mean time expected to build such a model using old simulation resources was much longer than that achieved with this simulator, at least for the complexity of the layouts modelled to the company EFACEC.

Another advantage of this simulator is it's the simple way how the warehouse elements are configured, as each of them has associated a *property box* where parameters can easily be modified.

What concerns the kind of results achieved with this simulator, one can say that they allow a good characterisation of the layout performances, mainly what is related with input and output processing rates, time processing distribution for palettes demands, vehicle occupation time, and some other statistical results. These results, together with the possibility of observing the behaviour of certain elements directly on the screen while the simulation is running, what many times is difficult to predict in practice, showed that this simulator is a very useful tool directed to warehouse designing and analysis. This explains the good results obtained with this simulator by EFACEC on several practical case studies.

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ii António E.S. Carvalho Brito,"*The Use of CAD Techniques in Configuring Visual Interactive Simulation Models: A New Approach for Warehouse Design*", Ph.D. Thesis, Cranfield Institute of Technology, U.K., 1992.

iii António E.S. Carvalho Brito,"*The Use of Computer Aided Design Techniques in Configuring Visual Interactive Simulation Models for Warehouse Design*", Journal of Decision Systems, Volume 1 - nº 2-3, Hermès, Paris, 1992

iv António E. S. Carvalho Brito, J. M. Feliz Teixeira, "*Warehouse visual simulation applied to a practical layout (Brasil)*", LASSIP, Faculty of Engineering of University of Porto, PORTUGAL, July 1998.

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# Warehouse visual simulation applied to a practical layout (Iran)

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**ABSTRACT**

In this paper we present the results of a case study made on warehouse characterisation by means of computer simulation techniques. In this study three different layout solutions were considered, one proposed by the ultimate Iranian client, and the other two designed and proposed by the Portuguese company EFACEC with the intention of achieving better performance and price than those on the Iranian's proposal. Each case have been analysed independently using as the base modeller a *visual and interactive warehouse simulator* early developed on this laboratory. This simulator uses an *object oriented approach*[i] and looks to the warehouse by an hierarchic decision level point of view, which permits an interesting separation of the responsibilities on the system. It is a modular approach, where each entity is responsible for its own integrity and functionality, and where the decision rules are separated on three fundamental levels: *element level*, *control level* and *management level*. The *simulator* was running on *Windows95/NT* operating system and have been developed using *Microsoft Visual C++*.

The present group of results are intended to characterise and compare the behaviour of the three different layouts in study, mainly their maximum rates of inputting and outputting material and the delay times expected in the most relevant processes.

## 1. Introduction

Warehouse automated systems are nowadays fundamental equipment to ensure the modernisation of production and distribution centres[ii], improving their flexibility and also to rise their processing capabilities in order to answer with more efficiency to the actual market demand.

The importance of simulation modelling in this field of industry is from all recognised[iii], anyhow, as the commercial software modellers seem to be or too simple to permit a reasonable modelling of the real system, or too complex to consent to build it in a proper time, for these two main reasons only few Portuguese enterprises stand making some efforts in the field of simulation.

Nevertheless, with the strong evolution of programming languages in the direction of *Object Oriented Paradigm*, given its decrease of price and its improving flexibility, and also due to the excellent tools to build the user interface, simulation starts to become practicable even in those cases which imply the development of a particular solution, and this case of study showed the facility to built such models based on some basic simulation tools early developed.

## 2. Objectives

The main objective of this work was to characterise the three layouts in study, named *Layout1*, *Layout2* and *Layout3*, later presented on this paper, mainly their maximum rates of inputting and outputting material and the delay times expected in the most relevant processes. Nevertheless, this work also have been a new test for the warehouse simulator modeller early developed on this laboratory, acting as a good practical case for evaluating its capabilities of modelling. Each layout had two different levels for material movement, as the racking system could also be accessed by two distinct floors on the warehouse, what implied the adaptation of the simulator software to include this new feature on future usage.

The performance tests made on each layout were bounded to the following maximum rates imposed by the ultimate Iranian client:

- Maximum input+output rate = 60 + 60 palettes/hour including 20 palettes/hour of manual input picking and 20 palettes/hour of manual output picking.

## 3. Method

For each layout, there have been a scaled representation on the modeller's interactive view using the appropriate drawing tools included on it. This representation followed the warehouse dimensions and all the element's parameters proposed by the company EFACEC and the Iranian client. The basic warehouse layout structure was presented by EFACEC in a scaled AutoCAD drawing.

The study was made analyzing the "grouped input+output" response of each layout in order to characterise its overall response profile. The input palettes rates on the system, as well as the output rates, were established to be a bit higher than the client request, what could let us observe the system working even under more charge than what was required. In each case, simulation was made to run during time enough to reach stabilised results.

In some cases the response of the layout was analysed in two different situations for the material positioning on the racking storage: *maximum* concentration, and *random* spread. This was achieved by including in the simulator a new parameter who was responsible for to impose the maximum action radius for each *racking vehicle* movement, what indirectly leaded to variations on the number of way exchanges per unit time, and so influencing the layout's input and output processing rates.

## 4. The basic layout and its elements

The basic characteristics common to the three layouts in study was the following:

- Warehouse rectangular dimensions = 140x80 m2
- Racking area = 20 ways of two side access racking.
- 1 fixed rate reception point + 1 manual reception point.
- Input conveyors zone serving the reception points.
- 1 fixed rate despatch point + 1 manual despatch point.
- 4 *Chariot vehicles* distributing along 20 raking ways.
- Input/Output access conveyors for each raking way.

Over this basic characteristics some changes were considered in each of the layouts, mainly the number *of raking vehicles* and *transfers* and the type of transference of palettes between the distribution *chariot* zone and the *racking* storage. Nevertheless all the layouts presented the following basis:

| **Model: layout Iran(1,2,3)** | |
|---|---|
| Nº of reception points: | 1 + 1 |
| Nº of despatch points: | 1 + 1 |
| Nº double racking ways: | 20 |
| | |
| **Conveyors characteristics:** | |
| Width (m) | 1.2 |
| Mean speed (m/s) | 0.2 |
| Unload time (s) | 0.5 |
| | |
| **Transfer table characteristics:** | |
| Width (m) | 1.2 |
| Action time (s) | 3.0 |
| | |
| **Chariot vehicle characteristics:** | |
| Initial acceleration (m/s2) | 0.4 |
| Mean speed (m/s) | 2.0 |
| Break acceleration (m/s2) | 0.4 |
| Mean time for loading (s) | 3.0 |
| Mean time for unloading (s) | 3.0 |
| | |
| **Racking vehicle characteristics:** | |
| Initial acceleration (m/s2) | 0.4 |
| Mean speed (m/s) | 3.0 |
| Break acceleration (m/s2) | 0.4 |
| Mean time for loading (s) | 10.0 |
| Mean time for unloading (s) | 10.0 |
| | |
| **Transfer vehicle characteristics:** | |
| Initial acceleration (m/s2) | 0.4 |
| Mean speed (m/s) | 0.5 |
| Break acceleration (m/s2) | 0.4 |
| Mean time for loading (s) | 10.0 |
| Mean time for unloading (s) | 10.0 |

Next figure represents a narrow view on one of the layout's reception zones served by conveyors, the kind of conveyors distribution zone to access the *chariots* zones and height out of the twenty raking ways where *racking vehicles* move. As one can see, there are two levels for the material flow, one closed to the layout's ground (level 0) and another in a "second" floor (level 1).

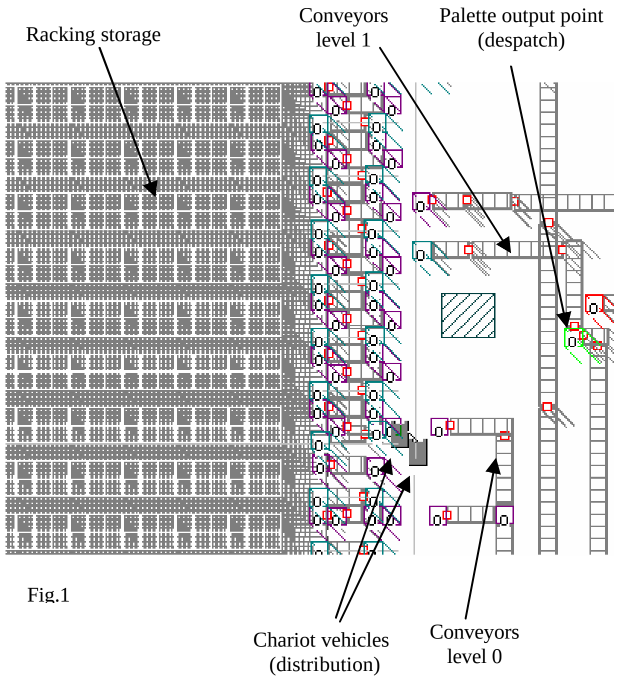



Fig.1

In the next figure (fig.2) one can see with more detail the two levels for material flow and the superposition of various conveyors on the access to the racking storage. Also is represented a pair of *chariots*, one responsible for the level 0 distribution and the other responsible for the same job at the level 1. Once in the racking storage areas, the material will be handled by *racking vehicles* (not represented on the figure).

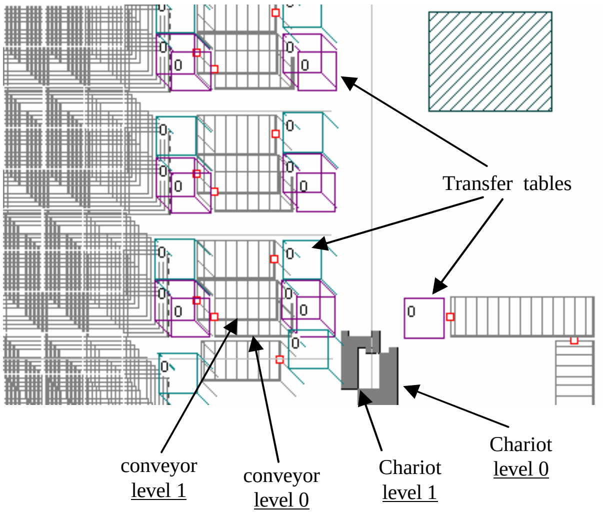



Fig.2

Finally, in the next figure is represented the back part of the warehouse, where one can see two *racking vehicles* as well as a *transfer vehicle*. This last vehicle is responsible for the *racking vehicle* exchanging of racking way, by first moving to the vehicle when necessary and then loading it and transferring it to the destiny way. In this figure is also visible some of the racking modules where the palettes are stored in the warehouse and five racking ways used by the *racking vehicles* to access the storage.

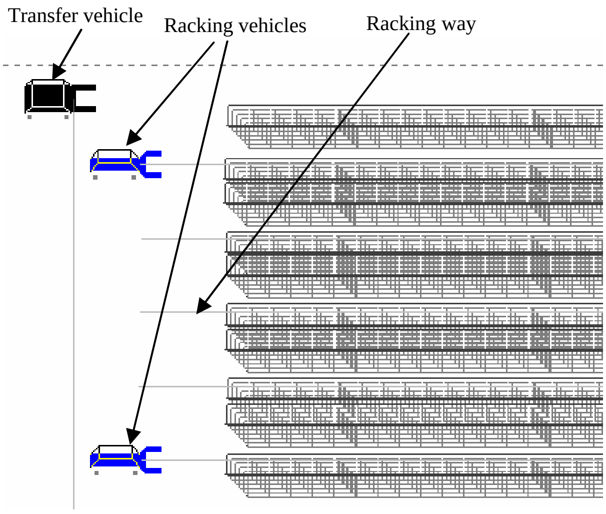



Fig.3

## 5. Results and discussion for separated layouts

Each of the four layouts proposed have been analysed separated and then the results compared between each other. Therefore in this section we present a more specific view on each layout followed by its correspondent discussion and results. Each layout was tested in *input+output response* mode, that is, while receiving orders for input and output material. Nevertheless, two different politics for conditioning the palettes on the storage have been considered, which indirectly was related with the rate variation on the *racking vehicle way exchanges per unit time*: *random politic* and *sever politic.*

In the *random politic* approach the palettes were picked or putted on the storage in a chosen random racking cell, while in the case of *severe politic* the chosen cell was conditioned by a "management" number (between 0 and 1) early introduced in the simulator. This number acted as a filter to choose the cell position on the storage.

Row data was first collected from the simulator results and then moved to a spread sheet program where histograms have been chosen to store the main results.

### 5.1 Results of *Layout1* (proposed by the Iranian client)

This layout was early proposed by the ultimate Iranian client and has the following characteristics over the basic ones presented in the last section of this paper:

- Two-level conveyors zone between *racking vehicles* and the *chariot* lines.
- 6 *racking vehicles* serving the 20 ways two-side access racking.
- 6 *transfers*, one for each *racking vehicle*.

The elements of this configuration have already been presented in the previous figures, where one can see the two-level conveyor zones for palette transference between the *chariot* lines and *racking vehicles* (fig.1 and fig.2), and the kind of *racking vehicles* used associated to a *transfer* (fig.3). However, in this layout there was one *transfer* for each *racking vehicle*, which is not the same condition as that represented in the figure 3.

As this layout (*Layout1*) presented a large number of *racking vehicles*, as well as one *transfer* for each of them, it have been tested with rates of palette input/output higher than those required by the client. This way we expected to estimate the deviation between the required performance and the effective capacity of that configuration.

So, it was imposed an input rate of 100 pal/hour, including manual inputs, and an output rate of 140 pal/hour also including manual output requests.

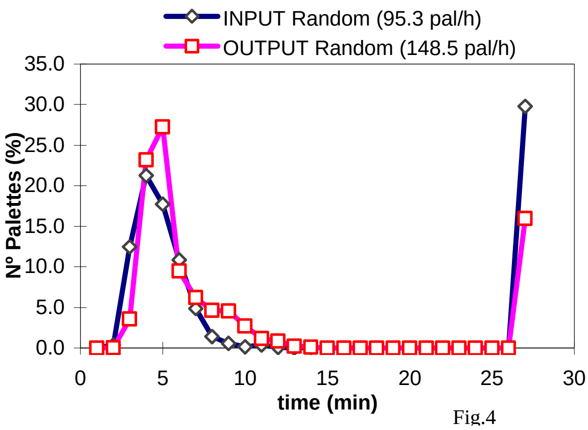



Fig.4

The layout was then simulated and its response observed and recorded (fig.4) during the time necessary for the stabilisation of the results. The “management” number used on the simulation was 0.5, what leaded to a case closed to the *random politic* approach.

The results obtained by simulation (fig.4) have shown the expected good performance of the system, as it have not been observed any kind of flow problems during the 10 hours of simulated activity. It have been detected, however, a large concentration of palettes waiting for processing either on the input and in the output points. Nevertheless, this was observed to be related with the extreme high rates imposed on the system, what have interfered with the capacity of delivery of the input/output conveyors group. This effect is can bee observed in the previous histogram as a large number of palettes with a processing time higher than 25 minutes.

The mean time for processing an input order stayed around 4 minutes with a spread variation between 3 and 8 minutes for most of the cases, for an input maximum rate of 95.3 pal/hour. For output processing the mean time was around 5 minutes with a variation between 3 and 10 minutes, for an output maximum rate of around 150 pal/hour.

By this results it became obvious that *Layout1* shows a significant higher capacity of processing that the 60+60 pal/hour required by the client, mainly due to the large number of *racking vehicles* and *transfers* used, what leaded to a fast response on processing input and output orders.

### 5.2 Results of *Layout2* (EFACEC's option A)

*Layout2* was the first layout proposed by the company EFACEC to the ultimate Iranian client. This option has the following characteristics over the basic ones for all the layouts:

- Two-level conveyors zone between *racking vehicles* and the *chariot* lines.
- 3 *racking vehicles* serving the 20 ways two-side access racking.
- 1 *transfer* serving all the *racking vehicles*.

As one can see, the difference between this configuration and the previous one is the number of *racking vehicle* elements considered as well as the number of *transfers* used. So, the configuration of this layout (*Layout2*) stays very similar to that presented on the previous figures (fig.1, fig.2 and fig.3).

As in this case the layout is expected to show a performance closer to the client demands, due to the reduction on the number of vehicles, it have been simulated within small rates of input/output than the previous case. For the same reasons this case was simulated in the two different conditions of management: *random politic* and *severe politic*. However, in the two cases have been imposed a rate of 60 pal/hour in the group of input points (40 pal/hour normal + 20 pal/hour manual), and the same rate imposed on the output points group.

The number of *racking vehicles* was reduced to 3, and there was only one *transfer* to serve all these *racking vehicles*.

The results for the *random politic* approach, which have been simulated during 10 hours of simulator time, are condensed on the following histogram:

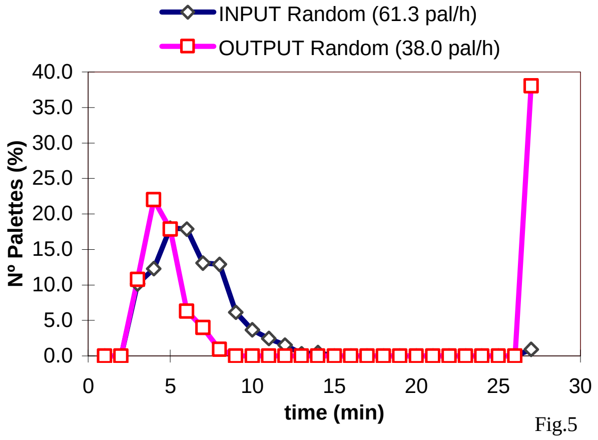



Fig.5

By these results one can conclude this layout was not enough fast to process all the required output orders at the imposed rate of 60 pal/hour. In fact, even if in the case of input processing the rate observed (61.3 pal/hour) in simulation was near the requirements, the output showed only a possible maximum processing rate of 38.0 pal/hour. As one can see from the same histogram, the system was even not able to start to process a large number of output palettes (time>25 min).

Anyway, in this *random politic* case the observed racking exchange way rate was 14.7 exch/hour/vehicle, which is far from the “management” levels considered normal in EFACEC company, what could mean the requirements maybe would be satisfied considering a higher level “management” politic.

***

In fact, simulating the same layout with a more *sever politic*, which in the case leaded to 5.8 exch/hour/vehicle, the observed rates have almost reached the client requirements, stabilising at 61.6 pal/hour for inputs and 60.0 pal/hour for outputs after 14 hours of continuous simulation time. These results are resumed in the next histogram.

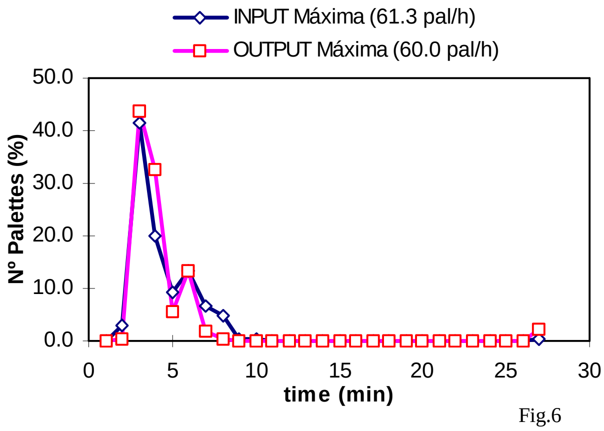



Fig.6

From these results is evident that in the conditions of a *sever politic* of the order of 5.8 exch/hour/vehicle the mean time for processing input and output requests are reduced and no palettes will be waiting for processing. This means that in such a condition one can expect this layout to work properly fulfilling the required client rates.

As the unique disadvantage of this layout we would say it is the fact that these results only could be obtained using a *severe politic* on managing the storage cells choice, what means the system will not be used in a "relaxed" condition.

### 5.3 **Results of *Layout3*** (EFACEC's option B)

*Layout3* was the second layout proposed by the company EFACEC to the ultimate Iranian client. In this option the two-level conveyors between the *chariot* lines and the *racking vehicles* was replaced by *transfers* equipped with conveyors. The new characteristics are the following:

- 3 *transfers* with conveyors between *racking vehicles* and the *chariot* lines.
- 3 *racking vehicles* serving the 20 ways two-side access racking.

In this configuration the *transfers* play two different roles: to transfer the palettes from the *chariot* distribution zone to the *racking vehicles* zone, and at the same time to ensure the transference of the *racking vehicles* when they need to change to a different racking way. This fact implied new developments on the simulator software with the intent of adapting it to this new *transfer* interface case.

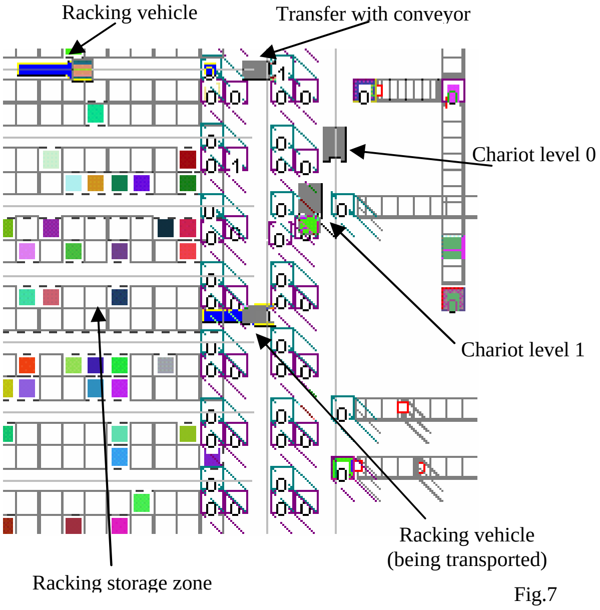
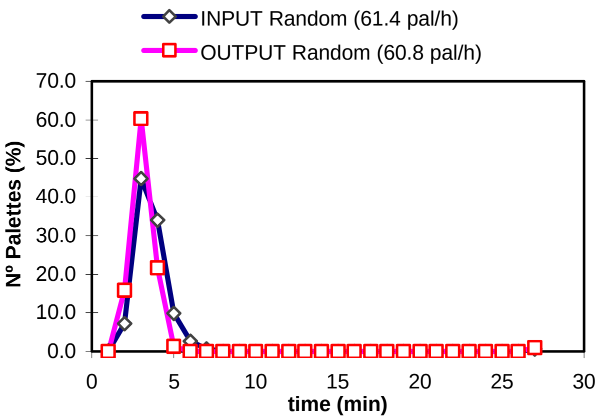



Fig.7

As one can see on the previous figure (fig.7), this layout is significantly different from the other two, and the main idea was to concentrate the work on the transfers to increase the overall processing layout's speed.

As this configuration early seemed faster that the previous EFACEC's option, the layout was simulated using only the random politic approach, as this approach represents the worst case for layout response.

The correspondent result are shown in the histogram:




After 10 hours of simulated continuous activity this layout showed that could process all the input and output orders, leading to an observed 61.4 pal/hour input processing rate and to 60.8 pal/hour output rate. This values were obtained with a random politic to which corresponded 22.4 exch/hour/vehicle, what means that even better performances would be achieved considering a more sever politic.

The mean time for processing input or output orders of around 3.5 minutes showed that this layout was the faster of all the considered ones, and at the same time it is a "relaxed" configuration for the client proposes.

## 6. **Conclusions**

From comparing the three proposed layouts one can conclude that the last option (*Layout3*) is far the most interesting configuration, as it will guarantee the performances required by the ultimate client within a good security margin of values. Also this solution is preferable, at least to the one proposed by the Iranian client, due to the reduction on the number of vehicles used. At the same time, around 60 conveyors could be eliminated from the layout.

What concerns the EFACEC's option A (*Layout2*), one can say this layout would also meet the requirements if used within *sever politic* of warehouse management, anyhow, some problems could arise on using it high demand situations.

Concerning the original layout (*Layout1*) this study have shown an excessive usage of vehicle resources, what means that is a super-dimensioned solution.

**References:**

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[i] J. M. Feliz Teixeira, António E. S. Carvalho Brito, "*Introduction to a warehouse visual simulator*", LASSIP, Faculty of Engineering of University of Porto, PORTUGAL, November 1997.

[ii] António E.S. Carvalho Brito,"*The Use of CAD Techniques in Configuring Visual Interactive Simulation Models: A New Approach for Warehouse Design*", Ph.D. Thesis, Cranfield Institute of Technology, U.K., 1992.

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# Warehouse visual simulation applied to a practical layout (Brasil)

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**ABSTRACT**

This paper presents a simulation study made on the project of a warehouse layout, designed by the Portuguese company EFACEC with the purpose of installing it in Brasil. The case have been analysed using *Visual and Interactive Modelling*, conceiving the elements and processes in the warehouse with the same base philosophy of management and control systems this Portuguese enterprise uses in building automated warehouses.

The results presented here where achieved by developing an *object oriented simulator*[i] where one could look to the warehouse by a hierarchic decision level point of view, which allowed a more realistic separation of the responsibilities on the system. It was a modular approach, where each entity was responsible for its own integrity and functionality, and where the decision rules were separated on three fundamental levels: *element level*, *control level* and *management level*. In this perspective the other components of the simulation were reduced to methods of material handling between *elements* and to some decision rules implemented in some more or less complex algorithms. The chosen operating system was the *Windows95/NT* and the programming language the *Microsoft Visual C++*.

The present results, achieved by the usage of such a simulator, had the intention of characterising the behaviour of the warehouse, mainly its maximum rates of throughput material and the expected delay times for the most relevant processes.

## 1. Introduction

Warehouse automated systems are nowadays fundamental equipment to ensure the modernisation of production and distribution centres[ii]. That is a rule for improving their flexibility and also to rise their processing capabilities in order to answer with more efficiency to the actual market demands.

The importance of simulation modelling in this field of industry is from all recognised[iii], anyhow, as the commercial software modellers seem to be or too simple to allow a reasonable modelling of the real system, or too complex to build it in a proper time. For these two main reasons only few Portuguese companies are making efforts in the field of simulation.

Nevertheless, with the strong evolution of *Object Oriented* programming languages, given its decrease of price and its improving flexibility, and also due to the excellent tools to build the user interface, simulation is becoming practicable even in those cases which imply the development of a particular solution. This case study is an example of such a facility to quickly build a model with this kind of approach.

## 2. Objectives

The main objective of this work was to characterise a warehouse, mainly its maximum rates of throughput material and the expected delay times for its most relevant processes. Nevertheless, this work also have contributed for improving the warehouse simulator modeller early developed on this laboratory, acting as a good practical case to test its modelling capabilities.

The maximum material processing rates proposed by the client were the following:

Single warehouse input rate = 165 palettes/hour
Single warehouse output rate = 165 palettes/hour
Warehouse working input+output rate = 100 + 100 palettes/hour

## 3. Method

The simulation computer program developed for this case have acted over a scale representation of the layout designed and proposed by the firm EFACEC with the file format DWG (AutoCAD). Every element in the warehouse was previously defined following the client specifications and the original dimensions presented in the warehouse AutoCAD drawing. The layout had the following characteristics:

- Warehouse rectangular dimensions = 150x80 m2
- Racking area = 15 ways of two side access racking.
- Input conveyor zone = 5 reception points + 1 manual.
- Distribution conveyors serving the 15 racking ways.
- 2 transfer tables per each way of racking.
- Output conveyor zone = 1 despatch point.
- Rotating table to access the despatch point.
- 4 *Racking vehicles* serving the 15 raking aisles.
- 1 *Transfer vehicle* serving the racking vehicle group.

The study was made in four distinct phases with which we pretended to characterise the overall response profile of the warehouse layout:

- Single input material simulation mode.
- Single output material simulation mode.
- Grouped input + output material simulation mode.
- Estimation of the rate dependency on the number of *racking vehicles* aisle exchanges per time unit.

For each of the first three phases it have been imposed on the model a input (output) rate of palettes a bit higher than the required by the client in order to make it possible to force the system to its maximal performances, and then the simulation was made to run for time enough to reach stabilised results.

Concerning the last phase, the estimation of rates dependency on the number of aisle exchanges per unit time, we have decided to consider the system working in output palette mode, as we expected this dependence to be maintained in the other working modes. This was achieved by including in the simulator a new parameter that was responsible to impose the maximum action radius for each *racking vehicle* movement, which indirectly leaded to variations on the number of aisle exchanges per unit time. This number, however, have always been calculated by the simulation computer program in the end of each running, and not by any kind of direct action of the user.

## 4. The layout and its elements

The following layout parameters and elements characteristics were considered in the simulation modelling:

| | |
|---|---|
| **Model: layout Brasil** | |
| Nº of racking palette cells: | 18900 |
| Nº of *Racking vehicles*: | 4 |
| Nº of *Transfer vehicles*: | 1 |
| Nº of reception points: | 5 + 1 |
| Nº of despatch points: | 1 |
| Nº double racking ways: | 15 |
| **Conveyors characteristics:** | |
| Width (m) | 1.2 |
| Average speed (m/s) | 0.2 |
| Unload time (s) | 0.5 |
| **Transfer table characteristics:** | |
| Width (m) | 1.2 |
| Action time (s) | 3.0 |
| **Rotating table characteristics:** | |
| Width (m) | 1.2 |
| Action time (s) | 5.0 |
| **Racking vehicle characteristics:** | |
| Initial acceleration (m/s2) | 0.4 |
| Average speed (m/s) | 3.8 |
| Break acceleration (m/s2) | 0.4 |
| Average time for loading (s) | 10.0 |
| Average time for unloading (s) | 10.0 |
| **Transfer vehicle characteristics:** | |
| Initial acceleration (m/s2) | 0.4 |
| Average speed (m/s) | 1.0 |
| Break acceleration (m/s2) | 0.4 |
| Average time for loading (s) | 10.0 |
| Average time for unloading (s) | 10.0 |

Next figure represents a small view on the layout's reception zone served by conveyors, the kind of conveyors distribution zone to access the racking zones and three out of the fifteen raking aisles where *racking vehicles* move.

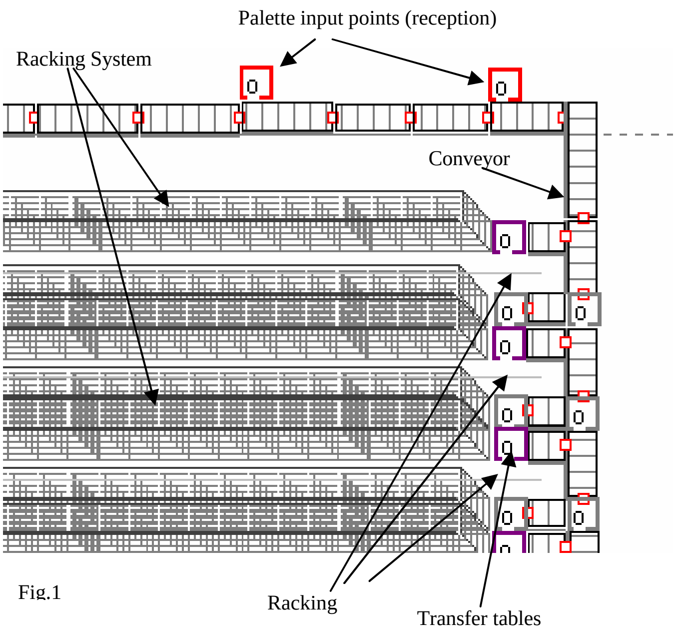


Fig.1

In the next figure the output (despatch) zone of the layout is shown, also served by conveyors and with only one output palette point. Also in this figure the racking modules are represented and some racking aisles, as well as the transfer tables used to interface the conveyors distribution zone with the *racking vehicle* access points. These vehicles receive the material in palettes coming from the reception zone by a transfer table interface point, and the same holds for the process of outputting material to the despatch point.

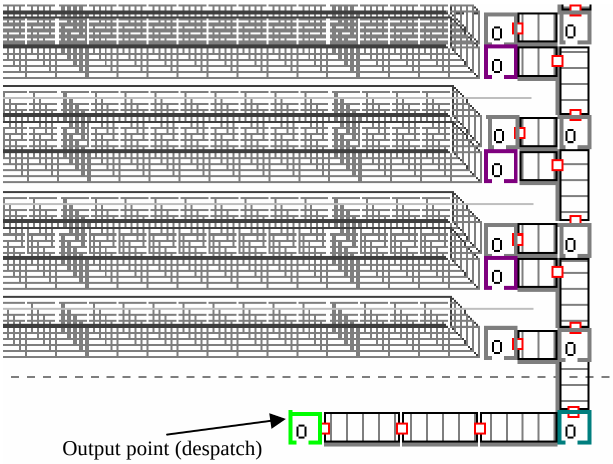


Fig.2

Finally, in the next figure is presented two out of the four *racking vehicles* as well as the *transfer vehicle*. This last vehicle is responsible for changing of aisle the *racking vehicles*, by first moving to the vehicle when necessary, and then loading it and transferring it to the next aisle. In this figure is also visible some of the racking modules where the palettes are stored in the warehouse and five racking aisles used by the racking vehicles to access the storage.

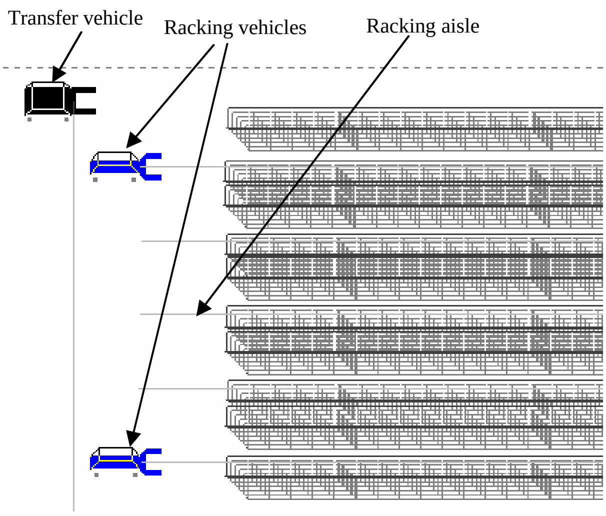


Fig.3

## 5. Results and analysis

Due to the four different phases on testing the layout, the results will be presented in the following sequence: *input response*, *output response*, *input+output response* and *output rate variation* with the racking aisle exchanges per time unit.

Row data first collected from the simulator was moved to a spread sheet program where histograms have been chosen to store the main results. In this section each case will be described by means of its boundary conditions as well as discussed while presenting the results.

### 5.1 Single input response

The single input palette rate was simulated imposing to the group of 5 input points an overall input of 200 palette/hour, reducing the output demand to 2 palette/hour and then observing the system evolution in time. It have been considered two different situations concerning the action radius of each *racking vehicle*: first imposing a minimum number of racking aisle exchanging, (what leaded to a calculated value of 2.04 exch/hour/vehicle), situation which could be compared to a sever politic on choosing the racking places to store the material, and in the second case considering this choose to be random.

In the first case an 11.58 hours continuous period of activity was simulated, while for the second case the results were observed to stabilised after 6.96 hours of simulation time. Each of these results is resumed in the following histogram:

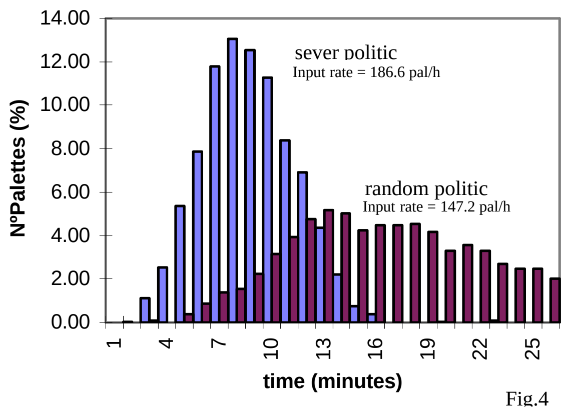


Fig.4

- In the case of using “sever politic” for choosing the racking places to store the material, which leaded to 2.04 exch/hour/vehicle, the average input rate observed after 11.58 hours of continuous activity simulation was **186.6 pal/h**. Due to the extreme conditions of input demands this can be considered the <u>maximum input rate the layout allows</u>. In the histogram the time distribution for palette processing is plotted, in terms of percentage of overall number of palettes processed, and the results for this case shows an average value near 9 minutes for the layout to process a palette, in which one can expect a variation of ±7 minutes depending on the system’s input oscillation. This distribution shows a good symmetry around the average value, as can bee seen from the plotted points in the histogram, mainly because the “severe politic” condition implied a similar *racking vehicle* time consuming for almost all the input cases, as these vehicles most of the time stand in the same racking aisle. This fact also leaded to a low average time for processing the inputs.

- In the case of a “random politic” for choosing the palettes destiny the observed an average input rate after the 6.96 hours of simulated activity was **147.2 pal/h**. This situation leaded to a spread on the time processing distribution (same histogram), rising the average value to 16 minutes and the variation to ±11 minutes. Also this distribution shows less symmetry compared with the previous case, due to the natural broadening of time processing for each *racking vehicle* required by the “random politic” choosing for palette destination. The observed broadening was also due to the excessive input rate required, what caused some situations of congestion in the palette flow through the layout's conveyor network. In fact, the actual design of this layout's conveyor's distribution network let us suspect of this kind of problems when in excessive input conditions, as in some case the palettes have to wait too much time in the interface tables for the *racking vehicle* to pick them, thus producing a break in the material flow in the main distribution conveyors line.

### 5.2 Single output response

The single output palette rate was simulated imposing in the output point (despatch) a demanding rate near 200 palette/hour and minimising the inputs to around 2 palette/hour, and then observing the layout's behaviour in time. As in the previous case of single input rate, we have considered again the same two extreme situations on choosing the palette's origin racking cell, what leaded to two different situations for each *racking vehicle* working radius. For the "sever politic" it was observed a minimum in the racking aisle changing equal to 2.47 exch/hour/vehicle and a continuous activity time of 13.89 hours have been simulated. In the case of "random politic" the same working time have been considered (13.89 hours). The results are presented in the following histogram:

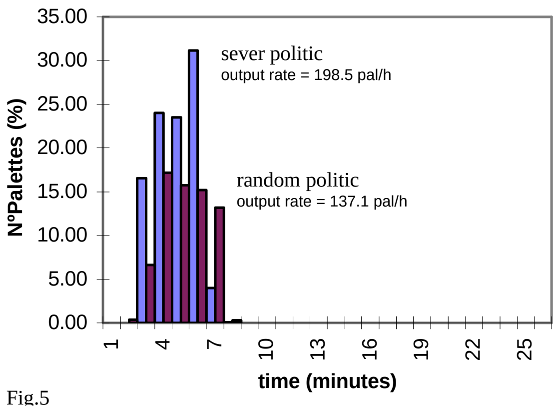


Fig.5

- Using a "sever politic" on choosing the palette origin inside the storage zone, which leaded to a racking aisle exchange rate of 2.47 exch/hour/vehicle, it was observed an average output rate of palettes of **198.5 pal/h**. This can be considered the maximum admissible output rate for this layout. In the histogram is presented the distribution for output palette time processing (fig. 5), which shows that the output process is faster than the input process. In fact, one can expect the output processing time to be between 4 and 6 minutes within a variation of ±3 minutes. This results show that the conveyor system has a good efficiency for outputting material, as in this case the interference of stopped distribution conveyors don't affect the flow to the output point as much as in the previous case of inputting material.

- In the case of "random politic" the output rate observed was reduced to **137.1 pal/h**, even if the output palette processing time remained very near to that observed in the case of "sever politic".

### 5.3 Grouped input+output response

In most practical situations in a warehouse the input processes stand together with output processes, that is, while some material is flowing into the warehouse storage, other material is flowing out to the output points. Therefore it was necessary to simulate the layout's behaviour in this case. The last two working modes were important to estimate the maximum rates for input and output in order to characterise the working limits of the layout, anyhow, only simulating the grouped input+output response could lead to more realistic data concerning the stand alone day by day processes.

In this case the input+output rate was simulated imposing in the input points group an overall input rate of 100 palettes/hour and defining in the output point a rate of 100 palettes/hour, then observing and registering the system's evolution with the time. Also in this case there was considered two extreme modes for palette choosing within the layout storage zone: "sever politic" and "random politic".

The "sever politic" working mode leaded to an observed rack aisle exchanging rate of 2.6 exch/hour/vehicle during the 8.34 hours of simulation time. In the "random politic" mode the layout running for 8.41 hours of simulator time. The results are presented in the following histograms.

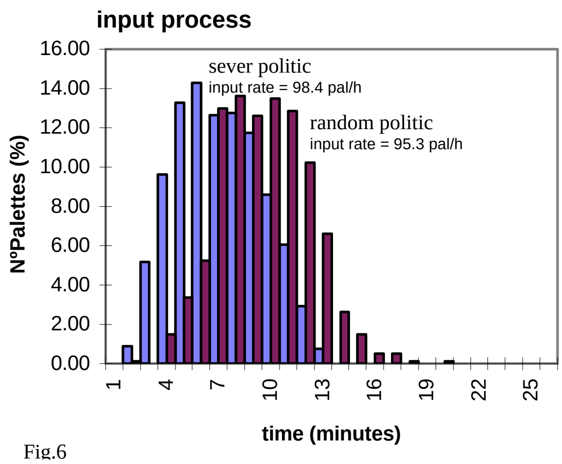


Fig.6

- For input processes and in "sever politic" working mode the observed input rate was **94.8 pal/h**. The output palette processing time distribution (fig. 6) showed the same tendencies as for single input response, although with a small performance increase due to the reduction of material processing times between 2 and 13 minutes. The average processing time was also reduced from about 9 to 7 minutes. This modest increase of performance is mainly due to the reduction on the overall input rate imposed on the layout's input points. This rate was 200 pal/h during the single input processing working mode and only 100 pal/h in the present case, what could reduce the system resources usage rate. It was also observed the output 100 pal/h process did not interfere significantly in the input process, what means the system was working in a "relaxed" mode.

- In the "random politic" mode it was observed a significant reduction on the input palette processing time (from 16 minutes with 200 pal/h to 9 minutes with 100 pal/h) what could rise the input processing rate to **95.3 pal/h**. Also the processing time distribution became less spread than in the previous case, approaching to the "sever politic" behaviour. These results show the conveyor distribution net plays an important rule on the system's performance when working with high input requirements.

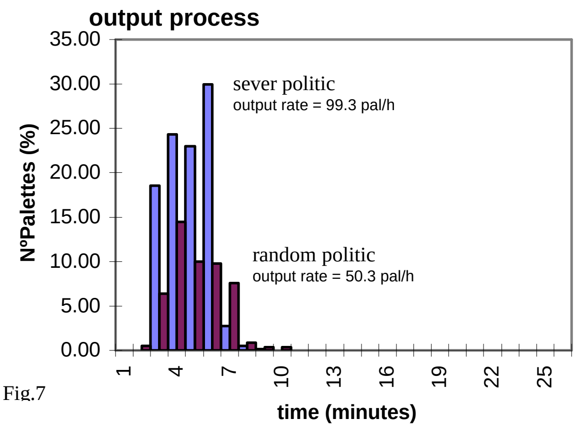


Fig.7

- For output processes in "sever politic" working mode (fig. 7) the layout behaved as if it would be working in single output mode, meaning that the input process does not interfere significantly on the output process at the actual 100 pal/h required level. Thus, the observed output palette processing rate was **99.3 pal/h** during the 8.34 hours of simulation time.

- In the "random politic" working mode it was also observed an output performance similar to the case of single output mode. Anyhow, it was detected a small increase of 3 minutes during the output processing of some few palettes. The observed output processing rate was **50.3 pal/h** during the 8.41 hours of simulated activity.

The previous results will be presented in the next two graphs by means of separated palette choosing "politic", what will let the reader understand better the system's behaviour on this two separated material processing modes. The graph of figure 8 represents the system response in "sever politic" mode, related with a racking aisle exchange rate of 2.5 exch/hour/vehicle, while the one of figure 9 represents the response observed in during "random politic" working mode, which leaded to an observed value of 26 exch/hour/vehicle for the racking way exchange rate.

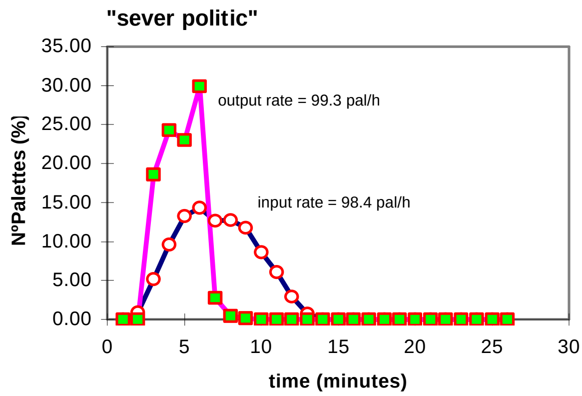


Fig.8

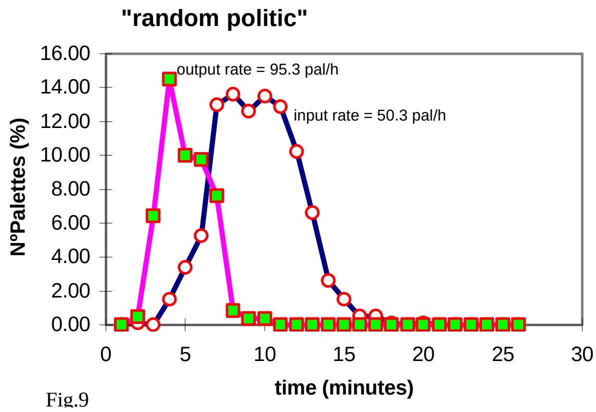


Fig.9

### 5.4 Output rate variation with the racking way exchange number

The previous results were referred to the two extreme working situations named "sever politic" and "random politic". The "sever politic" let us characterise the system's behaviour in its maximum processing capacity, while the "random politic" let us observe its performance in less demand situations. Anyhow, it seemed interesting to try to predict how the system would behave between these extreme working modes, what leaded us to study the layout's output rate variation with the racking aisle exchange rate variation. With this results we pretended to quantify the expected layout's response by means of different choosing palette's position criteria, thus leading to different storage material management criteria. One can say a "moderate sever politic" will correspond to 4 exch/hour/vehicle racking aisle exchange rate (or number), while in a practical "moderate politic" this value could be between 8 and 10 exch/hour/vehicle.

Thus, the system was sampled 15 times in single output material mode while in different situations of racking vehicles action radius, a parameter early introduced in the simulation program. Each time this parameter was changed the system have been simulated during a continuous working activity of about 14 hours of simulation time, and the number of racking way exchanges was calculated by the program at the end of each simulation run.

The results of this testes are presented in the next graph (fig.10) where 2.47 exch/hour/vehicle corresponds to the “sever politic” and 25.58 exch/hour/vehicle to the “random politic”.

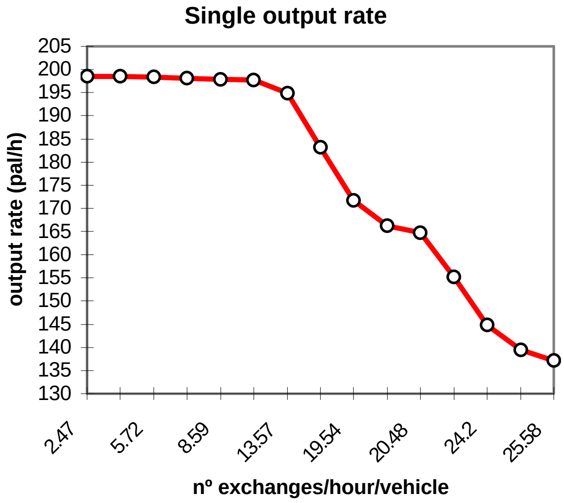


Fig.10

As it can be understood by the data plotted on this graph, the output rate stays more or less stable around its maximum value till 10 exch/hour/vehicle, meaning the system is expected to maintain its performance independent of working in a “sever politic” mode or even in a “moderate politic” mode. Thus, the management criteria for choosing the palettes on the storage zone will not interfere significantly to the system’s performance on these sort of conditions. This first result was expected as in this situation the *Transfer* usage time would be diluted on the usage time of the group of *racking vehicles*. Indirectly this is due to the long extension of each racking way as well as to the high processing level asked to the system. The significant decrease of output processing rate observed around 10 exch/hour/vehicle was due to the obvious increasing on *Transfer* usage when the palettes start to spread around more than two racking aisles, implying a substantial increasing on the *racking vehicle* displacement length, thus increasing the time for processing an output palette.

## 6. **Conclusions**

From the point of view of the client requirements this study could let us conclude the layout proposed is able to guarantee the requirements, at least within an expected deviation of ±3 pal/hour rate. Anyway, it was observed a certain responsibility on the conveyor network for the spreading and increasing of the input palette processing time, mainly during high input requirement rates. However this interference was yet very reduced when the input requirements are made low, what means the layout is expected to work properly within the conditions proposed by the client.

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[i] J. M. Feliz Teixeira, António E. S. Carvalho Brito, “*Introduction to a warehouse visual simulator*”, LASSIP, Faculty of Engineering of University of Porto, PORTUGAL, November 1997.

[ii] António E.S. Carvalho Brito,"*The Use of CAD Techniques in Configuring Visual Interactive Simulation Models: A New Approach for Warehouse Design*", Ph.D. Thesis, Cranfield Institute of Technology, U.K., 1992.

[iii] António E.S. Carvalho Brito,"*The Use of Computer Aided Design Techniques in Configuring Visual Interactive Simulation Models for Warehouse Design*", Journal of Decision Systems, Volume 1 - nº 2-3, Hermès, Paris, 1992.

# Introduction to a warehouse Visual simulator

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**ABSTRACT**

Here we present an introduction to the work we have developed with the mainly intent of conceive a *Visual and Interactive Simulator Modeller* for warehouse simulation.

In the approach presented here, the different elements in a warehouse, as well as the processes they are related with, were based on warehouse systems and control systems the Portuguese company EFACEC S.A. uses in its process of building warehouse systems.

In this paper an initial reference is made to the simulation paradigm chosen *(discrete simulation)* and also to the method used for representing the flow of time (*next event)*.

The chosen operating system was the *Windows95/NT* and *Microsoft Visual C++* the programming language. So, the conception of the modeller has been developed on an *Objected Oriented Programming* basis (OOP), where there have been included a User Graphic Interface to permit an easy way of drawing and configuring the layouts.

This work also establishes the basis of a more general conceptual modelling using *Object Oriented Simulation* with the intent to be used as a good simulation start point for other future modellers. In fact, from this work resulted a simulation structure that can be easy readapted to a large number of different simulation cases.

## 1. Introduction

Warehouse automated systems are nowadays fundamental equipment to ensure the modernisation of production and distribution centres[i]. That is a rule for improving their flexibility and also to rise their processing capabilities in order to answer with more efficiency to the actual market demand.

The importance of simulation modelling in this field of industry is from all recognised, anyhow, as the commercial software modellers seem to be or too simple to permit a reasonable modelling of the real system, or too complex to consent to build it in a proper time, for these two main reasons only few Portuguese enterprises stand making some efforts in the field of simulation.

Nevertheless, with the strong evolution of programming languages in the direction of *Object Oriented Paradigm*, given its decrease of price and its improving flexibility, and also due to the excellent tools to build the user interface, simulation starts to become practicable even in those cases which imply the development of a particular solution.

In this work a warehouse is seen from a hierarchic point of view, which permits a more realistic separation of the responsibilities of its behaviour. It is a modular approach, where each entity is responsible for its own integrity and functionality, and where the decision rules are separated on three fundamental levels: *element level*, *control level* and *Management level*. In this perspective the other components of the simulation are just reduced to methods of material handling between *elements* and to some decision rules that can be implemented in some more or less complex algorithms.

With this work we intended to restructure certain concepts applied to warehouse simulation, and that those concepts could lead us to finally develop a warehouse object oriented simulator software.

### Event simulation

As an brief introduction to the simulation methods used on this work it is important to refer we have chosen the *discrete simulation*, what means we are interested on representing the state of the system only in certain instants of the time. This method, when can be applied, usually conducts to a less complex formulation of the problem compared with, for example, continuous simulation techniques. However, there exist two different methods in discrete simulation to represent the time flow on the system (or the flow of the independent variable) (Pidd[ii]):

- *Time Slicing*, where the states of the system are sampled with a certain fixed frequency.

- *Next Event*, where the time advances to the next instant where there will be a changing in the state of the system.

Usually the *Next Event* technique is more efficient, as the sample frequency naturally adapts the way the states of the system change, what means one only have to analyse it in some relevant instants. The amount of calculations tends also to reduce in this kind of approach, implying fewer sources for accumulating errors.

The choice of this technique was due to the observation of the behaviour of warehouse systems, where processes develop in a discrete manner. By the other hand, this technique was early proposed also due to the deep tradition on *next event simulation* of this laboratory[iii], where it have been used for one decade to simulate various practical cases.

### 1.1 Concepts of entity and event.

The overall state time flow of any real system can be considered as the summation of some partial states of the elements of that system, elements which here we call *entities*. In that sense, *entities* can be, for example, the workers and the machines in a fabric, the clients and the staff personal in a post office, and, in general every elements that are able to show any state changes.

On the other hand, it is considered to happen an *event* in the instant of time an entity of the system changes it state. An *event* must then be responsible for starting a certain sequence of actions in the system, conducting or not to new events scheduled for the future. To this sequence of actions started by the event we call the *method* of that particular event.

In next event simulation literature one can easily find some didactic examples, as the well known philosophers case or the case of the haircutter. These cases are used to introduce the reader the basic concepts of simulation and also how to manage waiting lists. However, in this paper we have adopted another simple example for didactic purposes, which we have called "*the bus case*".

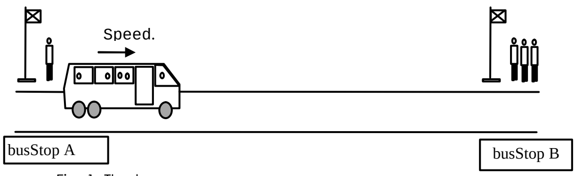


Fig. 1 The bus case

For now, lets suppose a bus the unique *entity* in the system. If at this moment we don't worry about the number of persons inside and waiting for the bus, lets consider the bus objective to go from bus-stop **A** to the bus-stop **B**. In this very simple example the bus can be found in one of the following two states: in march (we will call this state `MARCH`) while going from one stop to the other, and stopped (state `STOPPED`) while it is stopped near one of the bus-stops waiting for the clients to get out and to get in. The choice of these two states imply we must associate to the bus *entity* two different *events*: one to represent the instant of time the bus changes from `STOPPED` to `MARCH` (lets name it `EVENT_START`), and another to represent the change from `MARCH` to `STOPPED` (lets name it `EVENT_END`).

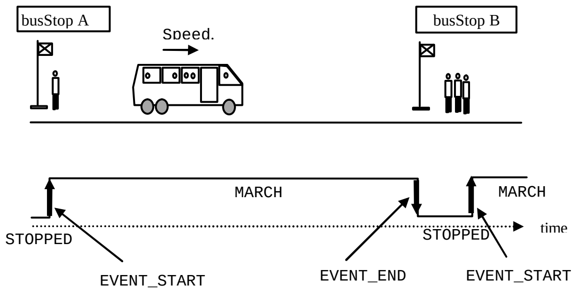


Fig. 2 The bus case with states and events

Each time an *event* happens it starts a group of actions, which defines the activity that will stand in the system till the time of the next *event*. This activity is defined in the *method* related with that *event*. This is the reason for associating to each *event* a *method* where it will stand a group of actions related with the required activity in the system.

Therefore, in the previous "bus case" the simulation will be resumed to the implementation of the following two methods:

- *Method* for the `EVENT_START` of the Bus *entity*:

```
Bus::Start()
{
```
  - ◊ *Set the state of the bus in* `MARCH`.
  - ◊ *Knowing the speed of the bus and the distance to the next BusStop, calculate the time to reach the next BusStop.*
  - ◊ *Schedule to that time the arrival of the* `EVENT_END`.

```
}
```

- *Method* for the `EVENT_END` of the Bus *entity*:

```
Bus::End()
{
```
  - ◊ *Set the state of the bus in* `STOPPED`.
  - ◊ *Calculate the time the bus will be stopped in the BusStop (dt).*
  - ◊ *If it is to continue, schedule another event* `EVENT_START` *for the actualTime+dt.*

```
}
```

In this simple case the activity of the system is reduced to the activity of a single entity: the bus. Anyhow, in practical systems one usually has to deal with many related entities, therefore the complexity of the model rises.

In general, before being executed, a event is first lined into the simulation *Event List* by means of a programming code method that receives the event and puts it in the proper place in that list ordered by increasing time. Here such method was named *Schedule()*. As we decided to identify an event with three parameters (the time when it is to occur, the identity of the event, and the entity responsible for executing the event), the *Event List* had to be considered as a list of objects where this information could be maintained. That was the reason for the creation of an elemental object that was named *SimTimeCell:*

```
class SimTimeCell : public CObject
{
 public:
    float         m_time;//event time
    UINT          m_event;//event number
    SimEntity*    m_pEntity;//entity to execute the event
};
```

The schedule of an event in the *Event List* is the responsibility of the *Schedule()* method, which will also order this list by increasing time and, in the case of events scheduled for the same time, by priority of execution. This priority was defined by the event identification number, a positive integer, where *zero* (0) represents the maximum possible priority. Any entity can use the *Schedule()* method to schedule events. The following example,

```
Schedule(t = 10, EVENT_START, pBus);
```

will result in the schedule of the event `EVENT_START` for time 10 associated with the entity `pBus`.

Once the event is scheduled in the *Event List*, its execution will be started by another method of the simulation named *Clock()*. This name was chosen for this method due to its responsibility of controlling the simulation time. This method removes the first event from the *Event List* and "sends" it to the associated entity to be executed. *Clock()* is then a loop on the simulator program code that will run while the *Event List* is not empty.

```
BOOL Simulator::Clock()
{
 SimClockCell* simClock;
 UINT evento;

 BOOL ret=FALSE;

 if(!m_eventList->IsEmpty())
   {
        ret=TRUE;

        //Remove the TOP event from the event list
        simClock = m_eventList->RemoveHead();

        //set the simulation time the same as the event execution time
        m_time = simClock->m_time;

        //"send"  the event to the related entity (to execute it)
        evento = simClock->m_event;

        simClock->m_pEntity->m_pSim = this;
        simClock->m_pEntity->Executa(evento);

        //Free memory
        delete simClock;
   }

 return ret;
}
```

## 2. Items in an automated warehouse

The components of a warehouse are in this approach grouped in *physical items*, that is the items occupying physical space in the warehouse, and *conceptual items*, those that represent conceptual forms of organisation, as *Jobs*, *Out Orders*, etc.

The *physical items* are grouped on:

- *Static items*
- *Dynamic items*

In the *Static items* one can include, for example, the reception and despatch zones of the warehouse, the paths for vehicle moving, the raking zones, the racking cells, etc. Belonging to the *dynamic items* group one considers the conveyors, the transfer tables, the workers, and all the kind of vehicles responsible for the movement of the material inside the warehouse. In general, the *static items* act as elements where the material stands, while the *dynamic items* are responsible for the transfer of the material between those *static* elements. In this approach, the warehouse can be thought as a black box receiving input and output tasks which starts an internal process of reorganisation involving the *physical* as well as the *conceptual items*.

## 3. Simulator structure

The *Simulator* object is the responsible for all the simulation process and was designed in accordance with the control and management informatic systems used by the company EFACEC on its warehouse systems. This idea was leading to the parallelism of concepts between those informatic solutions and the way the *Simulator* works, letting the user manage the simulation almost as he would manage the warehouse system.

Concerning the decision logic, we considered the following three distinct levels in the warehouse (fig.3): *element logic*, *control logic* and *management logic.*

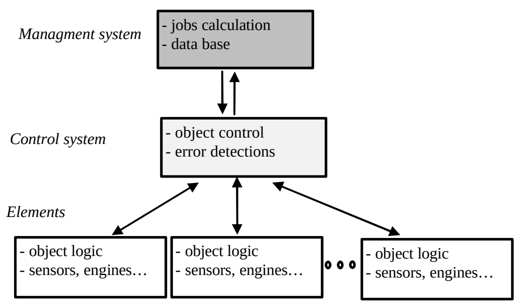


Fig. 3 Logic levels in a warehouse.

At the *elements* level the logic corresponds to the individual mechanism of the elements in the warehouse, that is, the way they work when apart from the system. The middle level, named *control system*, is related with the interaction with those elements, and deals with the criteria for exchange information between them. At the top level, named *Management system*, there is the logic related with the communication with the outside world, as well as the criteria to start jobs and also to access the warehouse model database.

Based on this idea the *Simulator* have been developed with a similar program code structure with the following correspondent levels (fig.4):

• ***SimWindow***, represents the physical space of the warehouse, where one can find the information about the conveyors, racking, aisles, vehicles, etc.,

• ***SimControl***, which represents the logic of the *Control system*,

• ***SimMaster***, which corresponds to the *Management system*. This block is responsible for the maintenance of the products information, output orders, input orders, and for the scheduling of the jobs of *dynamic elements* of the warehouse.

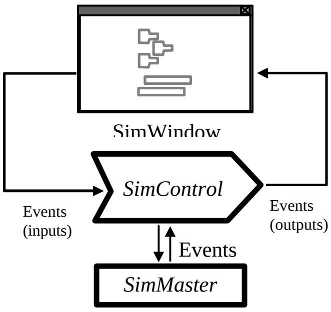


Fig. 4 Simulator structure.

### 3.1 Within the object *Simulator*

The *Simulator* is the object that controls the simulation, maintains the coherence of the time and "sends" to the entities the events to be executed. It is the *Simulator* the object that owns the reference for all the object lists on the system, those created by the operator before the simulation start as well as those created during run-time. It is also the owner of the simulation *Event list* and the methods concerned with its usage: the *Schedule()* to schedule the events, and the *Clock()* as the main simulation cycle.

One can say the *Simulator* has a "view" over the warehouse previously created by the operator, on which it executes the actions related with the events, then inducing state changes in the entities of the system, what leads to new orders and jobs appearing in the system, new spatial organisation for the material, new movements of the conveyors and vehicles…

The *Simulator* also owns the *SimControl()* and *SimMaster()* methods, which are deeply related with the *control system* and the *management system* of the warehouse, respectively.

#### 3.1.1 The *SimControl()*

This method is used by certain objects as the decision maker in certain specific circumstances, for example, by a conveyor in the instant the palette reaches one of its endpoints. One can say the *SimControl()* is a control block where there can be included the criteria usually implemented in the "Programming Logic Controllers" (PLCs) on a real installation. This means the logic related with control operations can be concentrated in one particular block of the simulator, making easy its access to any future criteria changes.

In figure 5 there is an example of the interaction between a conveyor and the *SimControl()* when a palette reaches the endpoint of the conveyor `conv1`. This conveyor sends the *SimControl()* the event END and the *SimControl()* then decides what to do.

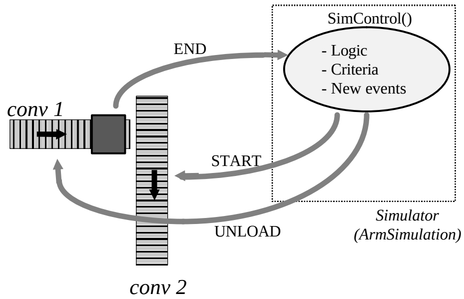


Fig. 5 Interaction of events with the *SimControl()*.

In the present case the *SimControl()* gives the conveyor `conv2` the order to start by sending it the event START, and then orders `conv1` to unload the palette by sending it the event UNLOAD.

This mechanism of control leads to a better organisation of the simulator, separating the program code by different levels of decisions, what will allow the change of control criteria without the need to change the conveyor's (or other element's) model code.

The next C++ code represents the basic structure of *SimControl()* where have been implemented the decision rule for when a palette reaches the end of a conveyor.

```
void Simulator::SimControl(time,event,pEnt)
float time;
UINT event;
SimEntity* pEnt;
{
  //if the entity is a conveyor:

  if(pEnt->m_tipo == CONVEYOR)
    {
     Conveyor* pconv = (Conveyor*)pEnt;
     switch(event)
     {
      case END:
      ////////////////////////////////////////////
      // Rule to follow when the palette reaches the end:
      // If exists an entity for the conveyor to unload and if
      // that entity is ready to receive the palette, then send the
      // conveyor the order to Unload(), else, stop it and put it in the
      // state WAITING.
      // Note: the unload can be to another conveyor or to a table.
      // If the unload is to a conveyor it is only necessary that this
      // conveyor is stopped and with no other palettes on it.
      // The unload to a table it is considered at anytime possible.
      // If the conveyor cannot unload, it will be stopped and putted
      // on the object waiting for unload list…
      ////////////////////////////////////////////
      float dt = pconv->m_tUnload;
      SimEntity* pUnload = pconv->m_pEntUnload;

      if(pUnload!= NULL)
      {
       //Unload to a conveyor:
       if(pUnload->m_tipo== CONVEYOR)
       {
        if(pUnload->m_state==STOPPED) //unload
        m_pSim->Schedule(time+dt,UNLOAD,pconv);

         else //Wait
           {
            pconv->m_state = WAITING;
            m_objWaitList.AddTail(pconv);
```

```
          POSITION pos;
          pos = m_objMovingList.Find(pconv);
          if(pos!=NULL)
              m_objMovingList.RemoveAt(pos);
         }
     }
     //Unload to a table:
     else
      m_pSim->Schedule(time+dt,UNLOAD,pconv);
    }
   //there is no unload entity. Let fall down the palette…
  else
     m_pSim->Schedule(time+dt,UNLOAD,pconv);

   break;

   default:break;
  }
 }//the entity was a conveyor…
}
```

### 3.1.2 The *SimMaster()*

This method includes the *management system* decision logic of the warehouse. It is responsible for maintaining the product information data, for ensuring the job distribution in the warehouse model and the for the good communication with the "surrounding world". It is this method the responsible for the interpretation of the input and output orders, for the choose of the cells involved in the flow of the material inside the warehouse, and for the scheduling of the jobs of the dynamic elements who will move the material from one place to another. Similarly to the previous case of *SimControl()*, this block of code *SimMaster()* plays the rule of a main decision management centre which objective is to handle the high level operations on the model.

As the main "manager" of the warehouse, the *SimMaster()* is then the owner of all the object lists taking part on the simulation process, by which it keeps a "view" from the overall model.

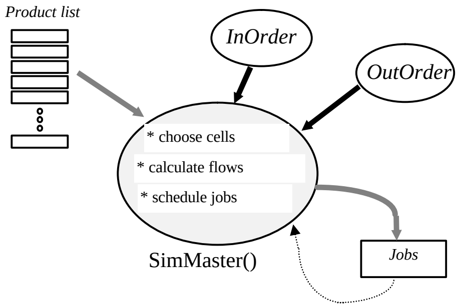


Fig. 6 Basic diagram of the *SimMaster() activity*.

Anyway, one of the most important tasks of the *SimMaster()* is to process the *input orders* as well as the *output orders* by means of analysing the list of products, the list of cells and its states, and the possible ways to take the material to its destiny. At this point it creates a new *job* to be given to the first *dynamic element* free (fig. 4.4).

As the decision criteria are implemented in this block of the simulator, certain objects send events to *SimMaster()*, then transferring the responsibility of the decisions to this high level logic processing "centre". That is the case of the transference of a *job* between different *dynamic elements*: each element is responsible for the execution of its part of the *job* and then it return the *job* to *SimMaster()* for that it can be given to the next *dynamic element*. The next figure represents one of these processes, in the case of moving a palette from an origin cell to a destiny cell involving vehicles and conveyors.

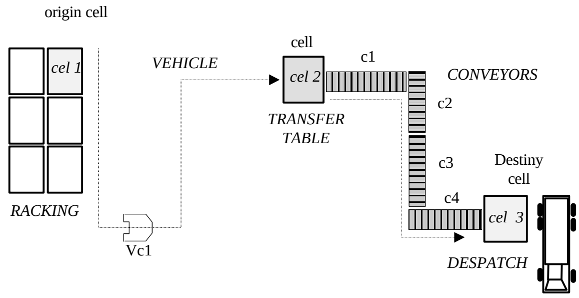


Fig. 7 Example of a simple output process.

In this example, first *SimMaster()* creates the following *job* that will be given to the vehicle `vc1`, as this is the *dynamic element* with access to the initial cell `cel1`.

| Type of SubJob | Number of unites | Type of unite | Product of the unite | Cell | |
|---|---|---|---|---|---|
| **LOAD** | 1 | PALETTE | P1 | **Cel1** | |
| **UNLOAD** | 1 | PALETTE | P1 | **Cel2** | **END** |
| **LOAD** | 1 | PALETTE | P1 | **Cel2** | |
| **UNLOAD** | 1 | PALETTE | P1 | **Cel3** | |

Once having the *job*, this vehicle starts to move in order to access the point of cell `cel1` where it will then load (LOAD) a palette containing the product `P1`. Finished the first line of the *job*, it will start to execute the next line related with the unload: it moves to the cell `cel2` where the palette will be unloaded (UNLOAD). Once executed the unloaded, the vehicle deletes its lines in the *job* and sends it back to the *SimMaster()* in the following form:

| Type of SubJob | Number of unites | Type of unite | Product of the unite | Cell | |
|---|---|---|---|---|---|
| **UNLOAD** | 1 | PALETE | P1 | **Cel2** | **UNLOAD (Done)** |
| **LOAD** | 1 | PALETE | P1 | **Cel2** | **UNLOAD (end)** |
| **UNLOAD** | 1 | PALETE | P1 | **Cel3** | |

When the *SimMaster()* receives back this *job* it will know the palette have already been unloaded in the cell `cel2`. As the *job* is not yet complete, *SimMaster()* will try then to find the next entity to whom the job can be given, that is, the entity who will be able to load the palette from cell `cel2` and take it to and unload it in cell `cel3`. In this process, *SimMaster()* have to analyse the possible paths of transport defined in the warehouse and then decide which path is to be chosen based on the decision criteria implemented. In this particular case *SimMaster()* will decide to give the remaining *job* to the conveyor `c1` after deleting the UNLOAD line on the head of the *job* subJob list. The remaining *job* will then be:

| *Type of subJob* | *Number of unites* | *Type of unite* | *Product of the unite* | *Cell* |
|---|---|---|---|---|
| **LOAD** | 1 | PALETE | P1 | **Cel2** |
| **UNLOAD** | 1 | PALETE | P1 | **Cel3** |

**UNLOAD (end)**

So, this conveyor loads the palette from cell `cel2` and moves it till reaching the conveyor `c2`. Then, the palette and the *job* are transferred to the next conveyor, who will be now responsible to move the palette till reaching the conveyor `c3`. Again the process repeats, till the palette and the *job* is transferred to the last conveyor `c4`. Finally, conveyor `c4` will move the palette till reaching cell `cel3` where it will execute the unload of the material. As there are no more lines to execute in the *job*, the *job* will be considered finished and the *SimMaster()* then notified by the conveyor `c4`.

The next C++ code represents the main structure of the *SimMaster()*, where one can easily understand the way the events are passed to this method.

```
void Simulator::SimMaster(time,event,pEnt)
float time;
UINT event;
SimEntity* pEnt;
{
/**************************************************
/*   If the entity who sends the event is a VEHICLE:
**************************************************/
 if(pEnt->m_tipo == VEHICLE)
   {
    Vehicle* pveic = (Vehicle*)pEnt;
    switch(event)
    {
     case JOB_END:
     ////////////////////////////////////////////
     // Here it would appear the code to run when a vehicle gets FREE
     ////////////////////////////////////////////
                 . . .
     break;

     default:break;
     }
   }

/**************************************************
/*   If the entity who sends the event is a conveyor:
**************************************************/
 else if(pEnt->m_tipo == CONVEYOR)
   {
    Conveyor* pconv = (Conveyor*)pEnt;
    switch(event)
    {
     case JOB_END:

     /////////////////////////////////////////////
     /
     // Here it would appear the code to run when a conveyor ends the
     JOB
     /////////////////////////////////////////////
     /
                 . . .

     break;

     default:break;
    }
   }

/**************************************************
/*   If the entity who sends the event is another kind of entity….
**************************************************/
                ...
}
```

### 3.1.3 The *SimMovie* (movement effects on simulation)

Certain entities on the simulation use the effect of movement to give the user a more realistic idea of the warehouse dynamics. That is the case of palette movement on the conveyors and the movement of the vehicles during the simulation run. All these "realistic" effects are sustained by the action of a new object in the simulator named *SimMovie*. Anyhow, the action of this object can be turned on or off, depending if the user wants the simulator to reproduce the visual movement of the dynamic entities on the computer display or not. So, this facility can always be turned off in order to speed up the simulation run. The object *SimMovie* is then an object reserved to display those movement effects that turn the visual simulation more closed to the behaviour of the real system. In order to make possible the action of *SimMovie* another event was defined in the system, named SIM_SHOW. If the operator decided to create the *SimMovie* object in the simulation, then this mechanism is activated, otherwise it stays disabled and no movement will be observed in the display. The structure of this object is the following:

```
class SimMovie : public SimEntity
{
 public:
   //Constructor:
   SimMovie(Simulator* pSim);

   //Event router:
   virtual BOOL Executa(UINT event);

   //Handler to the event SIM_SHOW:
   BOOL ShowON();
};
```

This object inherits from the base class *SimEntity* that will be presented soon on this paper. As already have been explained, the class *SimMovie* is responsible to handle the event SIM_SHOW routed to its method *ShowON()*. During creation, a pointer to the *Simulator* object is passed to *SimMovie*, through which it will have directly access to the list of objects moving in the simulation.

In the next figure it is represented a diagram of the mechanism which ensures the visual movement of the *dynamic elements* during the simulation run. This mechanism is enabled or disabled in the moment of starting the simulation process by creating or not an object *SimMovie*.

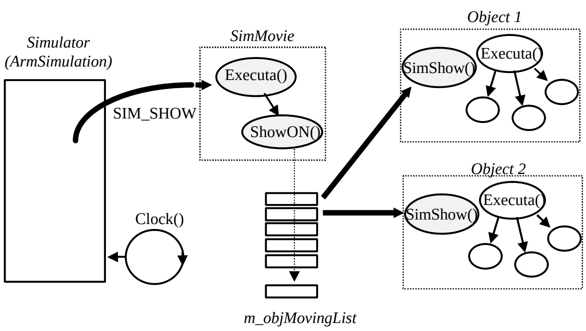


Fig. 8 Simulator mechanism for object moving in the display.

In this mechanism, when in the simulation *Clock() appears* the event SIM_SHOW, the *Simulador* sends it to the *SimMovie* object by calling its member function *Executa()*. This member function then calls its method responsible for handling the event SIM_SHOW, that is, the method named *ShowON()*. The activity of this method resumes to the call of the function *SimShow()* for each object in the simulator *object moving list* (`m_objMovingList`), which is the function responsible for the actualisation of the object on the display.

After, *ShowON()* calculates the next instant of time when is due the next display and schedules a new event SIM_SHOW to be executed in that moment of the future. The method *SimShow()* is presented in the following lines of code.

```
BOOL SimMovie::ShowON()
{
 SimEntity* pObj;

 //////////////////////////////////////////////////
 // Forces the representation on the display the moving objects…
 //////////////////////////////////////////////////
 POSITION pos;
 pos = m_pSim->m_objMovingList.GetHeadPosition();
 while(pos != NULL)
      {
       pObj = m_pSim->m_objMovingList.GetNext(pos);
       pObj->SimShow();
      }


 //////////////////////////////
 // schedule the next event SIM_SHOW
 //////////////////////////////
 float DT = m_pSim->m_DTime;
 m_pSim->Schedule(m_pSim->m_time+DT,SIM_SHOW,this);

 return TRUE;
}
```

## 4. <u>Passive</u> entities and <u>active</u> entities

During the simulation run one can consider two kind of entities running in the system: <u>passive</u> entities and <u>active</u> entities. <u>Passive</u> entities are considered those entities that are not responsible for the generation of any events, even if they can change their state, while <u>active</u> entities are those who plays an active role on event generation. A table, for instance, have been considered a <u>passive</u> entity, as it is viewed as a static element where the palettes can stay, while a conveyor or a vehicle have been thought as <u>active</u> entities, as they are responsible for the flow of the material along the warehouse, and then for the changing of the state of other related entities.

This section describes the mechanism by which the active entities on the system process their own events by inheriting from the base class *SimEntity*.

### 4.1 *Event* execution and class *SimEntity*

In this paper it was already described how to schedule events into the *event list* and how the simulator uses the method *Clock()* to remove them from that list, turning them executable. Nevertheless, nothing yet have been said about the mechanism subjacent to the event execution.

In such mechanism, when a certain event is to be processed by an object, the *Simulator* starts to call the method *Executa()* for that object, defined as virtual in the *SimEntity* class. In fact, this is the reason every <u>active</u> element on the simulation has to inherit from the base class *SimEntity*. Then, the execution of the event is started by the following statement:

```
m_pEntity->Executa(m_event);
```

which can be understood as “sending” the event `m_event` to the entity `m_pEntity`. Once the entity “receives” the event, the entity will search in its handle methods list the one designed to answer to that particular event, then calling it.

As an example, lets again think on the “Bus” case and in particular on “sending” the BUS entity the event `EVENT_END`. Let also assume there would be three events associated with the bus, named `EVENT_START`, `EVENT_WAIT` and `EVENT_END`, and then three handler methods named respectively *Start()*, *Wait()* and *End()*. When the *Simulator* retrieves from the *event list* the following *time cell* related with the event `EVENT_END`:

| | | |
|---|---|---|
| t = 10 | EVENT_END | pBus |

Then it simply sends the bus the event by executing the statement:

```
pBus->Executa(EVENT_END);
```

At this point the bus already “knows” which event is to process, and then it can choose the correct handling method defined and implemented on its object class. In this particular case the *End()* method would be chosen and the event finally processed. For all what was said here the virtual method *Executa()* defined in *SimEntity* class is considered as an <u>event router</u> (fig.9).

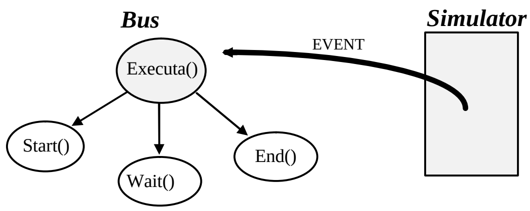


Fig. 9 Mechanism for executing events .

This mechanism was early proposed by Dirk Bolier [iv] in a publication concerning simulation libraries developed in C++, and it was adopted here due to its simplicity and practical efficiency. The method *Executa()* must have been declared <u>public</u> in the class definition of the object who will use it, in order to give the *Simulator* the possibility to access it. The remaining handler methods can most of the times be declared as <u>private</u> to that object.

As it is clear now the *SimEntity* class has the main objective of defining the basic functionality of any <u>active</u> entity in the simulation. That is why *Conveyor* objects as well *Vehicle* objects are made to inherit from *SimEntity*.

Nevertheless, in the class *SimEntity* have been included other kind of attributes useful to be used by any <u>active</u> elements on the simulation, as well as the definition of the method *SimShow()* related with the dynamic display of the object during the simulation run.

It is the following the *SimEntity* class structure:

```
class SimEntity : public CObject
{
 public:
   BOOL          m_livre; //generic use
   CString       m_nome;  //entity's name
   float         m_time;  //entity's time on the simulation
   UINT          m_estado;//entity's state
   Simulator*    m_pSim;  //pointer to the Simulator
   UINT          m_tipo;  //entity's type
   float         m_x;     //entity's x position
   float         m_y;     //entity's y position


   SimEntity(CString nome); //public constructor
   virtual void Serialize(CArchive& ar); //Serializer

 protected:
   SimEntity(); //private constructor

 public: //SIMULATION RELATED METHODS:
   virtual BOOL Executa(UINT event);//event router
   virtual void SimShow(); //movement display

  DECLARE_SERIAL(SimEntity)
};
```

## 5. Conclusions

This work leaded to the implementation of a visual warehouse simulator with which some results have been achieved mainly on simulating practical layouts developed by the firm EFACEC, what have shown the versatility and the easy use of the concepts presented here. There have been developed several layouts based on conveyor transportation and distribution of the material and also the action of vehicles with predefined paths interacting with palette racking systems.

The idea of separating the responsibility of decision criteria in the three referred levels (elements, control and "manager") have succeed and let us look at the warehouse as a modular and easy to modify system. The design of the entities was then thought as independent of the system as a whole, and so maintaining their functionality even isolated from the warehouse. This made possible to achieve a good degree of modularity as well as comfortable code portability.

In a certain point of view this approach lets us feel the *Simulator* more representative of the reality, as the events become property of the objects instead of considering the *Simulator* their owner. Also the hierarchy on the decision tasks lets us thought as managing a real warehouse system.

In particular concerning the *physical elements*, that is, conveyors, racking blocks, vehicles, transfer tables, etc., this work played an important role to start the development of future elements, in order to give the user the ability to access and choose objects from a list of standard warehouse equipment.

What concerns to the processing speed of this *Simulator* it was observed a practical value of ten (10) times faster than the real time flow, even if the implementation of the "three levels decision logic" early described could seem less efficient than if there would be no re-routing of the events between the objects and the *SimControl()* and *SimMaster()*. Anyhow, once nowadays computer systems performances are high and tend to increase, this question doesn't have to be considered relevant for typical problems of warehouse modelling.

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