SUSTAINABLE SOLUTIONS UNDER THE AXIOMATIC DESIGN PRINCIPLES: THE NEED FOR RESILIENCE

João Fradinho(*)\(^{,}\) António Gabriel Santos, António Gonçalves-Coelho, António Mourão
UNIDEEMI, Universidade Nova de Lisboa, Faculdade de Ciências e Tecnologia, Portugal
(*) Email: jmf@fct.unl.pt

ABSTRACT
By the end of the 20th century, a new and wide design concept emerged, sustainable design that is based on three main concerns: society, economy and environment. In an Axiomatic Design standpoint, sustainable designs are usually coupled. This paper is based on the assumption that the nature and the values of the design parameters used to describe the physical solutions conform to the required functionality and satisfy some economic and environmental requirements. This approach leads to suitable zones for the given requirements of different natures, and provides the knowledge that is required for design decision-making. Additionally, the approach warrants resilience to the adopted design solutions. The development of a rubber cork product is presented as an example. The attained results show that the proposed approach is appropriate.

**Keywords:** sustainability, resilience, axiomatic design, concurrent engineering, decision methods.

INTRODUCTION
By the end of the 20\(^{th}\) century, the international community became aware of the need to tackle the endless assault to the natural resources of the planet, by slowing down the consumption of natural resources and decreasing the pollution that is generated by the human activities. This awareness is transversal to all the human beings, including the engineers, who should therefore concern with the society, the environment and the economy, all along the life cycle of their design objects, as shown in Fig. 1.

![Fig. 1 - The triple bottom line of sustainability (adapted from (Chiu et. al., 2012))](image-url)

---

-1537-
The integration of performance with cost and environmental issues is presented in this work, as a means to provide the knowledge that is needed to implement the conceptual design stage. Design theories and methodologies were developed with the goal of formalizing, systematizing and structuring the designing process. One of those theories, the Axiomatic Design Theory, is based on stringent analytical methods (Suh, 1990). It provides a systematic and logical manner to conduct the design process, helping to avoid the traditional design-redesign cycles (trial and error) since the early evaluation of the hypothetical alternative solutions.

Axiomatic Design is based on two fundamental principles or axioms that allow identifying the “good” design solutions: the independence axiom and the information axiom. The search for “good” solutions should rely on the independence axiom, while selecting the final solution among several available “good” solutions should be based on the information axiom. Therefore, the AD axioms could support design decision-making.

Several resilience concepts are discussed in the next section. The importance of resilience in sustainable designs is exemplified by a rubbercork product design according to the Axiomatic Design principles.

THE CONCEPT OF RESILIENCE

In engineering, resilience is the ability of a material to absorb energy when deformed elastically and to completely release that energy upon unloading. Resilience is also a concern when we come to ecological and socio-political systems. Different interpretations of what resilience means might cause some misunderstanding. Thus, it is important to clarify the meaning of resilience. Walker et. al. (2004) discussed the significance of the word resilience in social-ecological systems, stating resilience is the “capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks.” According to the same authors, resilience has four components:

a) Latitude – the maximum amount a system can be changed before losing its ability to recover;

b) Resistance – the ease or difficulty of changing the system;

c) Precariousness – how close the current state of the system is to a limit;

d) Panarchy – due to cross-scale interactions.

Other definitions of resilience are found in the bibliography of different areas of knowledge, such as engineering design, sustainability, ecology, economy, and social sciences (see Table 1). Those definitions of resilience are very similar, no matter their origin, although some of them, such as the one of Kendra (2003), look much more like the engineering notion of toughness, which is the ability of a material to absorb energy and plastically deform without fracturing. The time that a system needs to recover after a disturbance occurs is also a characteristic of resilience. Two different systems could be resilient, however they might have different recovery times. Fig. 2 depicts some system functionality as a function of time. Next to the initial disturbance, a certain period is necessary until the system recovers and achieves a new state of equilibrium. In the context of this paper, resilience of a product or a system is meant as the ability to sustain, adapt and recover to an acceptable state after a perturbation occurs, even if this new state is different from the initial one. Any sustainable system might
be disturbed by a large variety of external interferences, and ideally it should be able to keep its responses at acceptable values, in order to be considered as being resilient. Hence, sustainability and resilience are akin, since resilience, the capacity to recover, is a manner to achieve sustainability.

Table 1 - A brief survey on the resilience definition under different disciplinary perspectives

<table>
<thead>
<tr>
<th>Perspective</th>
<th>Resilience definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social-ecological</td>
<td>Capacity of a system to absorb, disturbance and reorganize while undergoing change as to still retain essentially the same function, structure, identity and feedbacks.</td>
<td>Kinzing, 2006</td>
</tr>
<tr>
<td>General</td>
<td>Capacity of a system to tolerate disturbances while retaining its structure and function.</td>
<td>Fiksel, 2006</td>
</tr>
<tr>
<td>Economy</td>
<td>Capacity for an enterprise to survive, adapt, and grow in the face of turbulent change.</td>
<td>Fiksel, 2006</td>
</tr>
<tr>
<td>Organizational</td>
<td>Ability to sustain a shock without completely deteriorating.</td>
<td>Kendra, 2003</td>
</tr>
<tr>
<td>system</td>
<td>Ability of groups or communities to cope with external stresses as a result of social, political, and environmental change.</td>
<td>Adger, 2000</td>
</tr>
<tr>
<td>General</td>
<td>Ability to withstand a major disruption within acceptable degradation parameters and to recover within acceptable time and composite costs and risks.</td>
<td>Haimes, 2009</td>
</tr>
<tr>
<td>Ecological</td>
<td>Measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables</td>
<td>Holling, 1973</td>
</tr>
<tr>
<td>system</td>
<td>Ability to recover from, or resist being affected by, a setback, illness, etc</td>
<td>Oxford dictionary, 2007.</td>
</tr>
</tbody>
</table>
The importance of resilience in sustainable design is exemplified in the next section throughout a rubbercork product design, where the Axiomatic Design principles are used to conduct decision-making process.

**A SUSTAINABLE DESIGN EXAMPLE: THE RUBBERCORK PRODUCT**

Fradinho *et al.* (2009) presented a study on the development of a rubbercork composite for the manufacture of gaskets that was based on performance and cost. The goal of the current example is to extend the study to the use of the previously attained contour lines, in order to identify acceptable “performance zones” together with satisfactory “cost zones” and suitable qualitative “environmental zones” for a rubbercork product. On the contrary of the traditional standpoint of considering cost and the environmental factors as constraints, they are pro-actively considered as requirements that are impacted by several design parameters.

The approach consists in representing countor lines for performance and cost as functions of the same two design parameters. Due to the lack of data, the environmental factors, which depend on the very same design parameters, are considered qualitatively.

The phenomenological expressions that explain performance and cost are obtained through design of experiments and the corresponding contour lines are obtained. Fig. 3 depicts a schematic representation of the product design process.
The performance requirements are the tensile strength, $T$, and the compressibility, $C$, of the rubbercork product. The design parameters for performance and cost were investigated through design of experiments.

ANOVA was subsequently used to identify the key design parameters, which were found to be the density, $x_1$, the fraction of cork, $x_2$, and the size of the cork granules, $x_3$. The latter is a discrete variable with two values only (1-2 mm and 2-4 mm). After processing and statistical validation, the expressions for the tensile strength and the compressibility were found for each one of the two available granule sizes. The expressions for the 1-2 mm granule size are

$$T = 2.82 + 0.26x_1 + 0.12x_2 \quad (R=0.97) \quad (1)$$

$$C = 31.1 - 3.4x_1 - 2.3x_2 \quad (R=0.96) \quad (2)$$

The cost of rubbercork mainly depends on the market price of its ingredients. The cost in €/m$^3$, $C_m$, is given by

$$C_m = \frac{937.558 + 64.216x_1 + 106.417x_2 x_3}{1 + 0.075x_2}. \quad (3)$$

According to Axiomatic Design, the design equation for the rubbercork product is

$$\begin{bmatrix} T \\ C \\ C_m \end{bmatrix} = \begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix},$$

which represents a coupled design because the design matrix is fully populated with non-zero elements (Suh, 1990), which are represented by the symbol “$x$”. Since the size of the cork
granules, $x_3$, is a discrete parameter, one can split the design of Eq. (4) in two distinct designs, one of each cork granule size. The design equation of those two designs is of the form

$$
\begin{bmatrix}
T \\
C \\
C_M
\end{bmatrix}
= 
\begin{bmatrix}
x_1 & x_2 \\
x_1 & x_2 \\
x_1 & x_2
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix},
$$

and we have again a coupled design as per AD’s theorem 1 (Suh, 1990).

Overlaying the contour line families obtained from Eq.s (1~3) allows finding regions of interest for the values of performance and cost.

To illustrate the procedure, let us consider that we want to produce two rubber-cork products, made of 1-2 mm cork granule size, with the following characteristics:

- **Product 1**: $T_{\text{min}} = 2.8$ MPa, $C = 25 \sim 30\%$;
- **Product 2**: $T_{\text{min}} = 2.7$ MPa, $C = 30 \sim 35\%$.

The grey areas of Fig. 6 and Fig. 7 obtained from Eq.s (2~4) indicate values of the design parameters “density”, $x_1$, and “fraction of cork”, $x_2$, that satisfy the performance requirements at an acceptable cost, while the black areas indicate the zones of lower cost.

![Fig. 4 - Tensile strength, compressibility and cost zones for Product 1 (Fradinho et al., 2009)](image1)

![Fig. 5 - Tensile strength, compressibility and cost zones for Product 2 (Fradinho et al., 2009)](image2)
In what to the environment concerns, granulated cork is a constituent with amazing properties. Cork oak converts CO$_2$ into oxygen and carbon compounds through photosynthesis. From this viewpoint, a high consumption of cork corresponds to a positive contribution to the environment, so that our environmental requirements are to use as less energy as possible and as much cork as we could. One should notice that the cork oaks are not sacrificed to extract the cork. On the other end, the higher is the density of the product, the higher is the energy consumption of the rubbercork production process.

As the surfaces depicted in Fig. 4 and Fig. 5 have the specific weight, $x_1$, and the relative amount of granulated cork, $x_2$, as the orthogonal axes, then the preferred areas are located in the upper left part of both figures in the environmental point of view.

Thus, the combination of the data contained in Fig. 4 and Fig. 5 shows the upper left area of black areas as the most suitable for the two values of the design parameters leading to the development of products within integrated sustainable design.

On the contrary to the habit of considering the cost and environmental factors as constraints, this paper considers both as requirements. Performance, cost and environmental factors depend on the same design parameters, which leads to a coupled design.

CONCLUSION

The present methodology supports decision-making in the conceptual step of a sustainable design, by simultaneously integrating data on performance, cost and environmental factors, thus promoting resilience. This is an appropriate manner to deal with coupled designs in which requirements of different natures are attained by adjusting the very same design parameters. This allows identifying zones that warrant similar product behaviour, including the cost, with different values of the design parameters.

ACKNOWLEDGMENTS

The authors gratefully thank the sponsorship of Fundação para a Ciência e Tecnologia through the Strategic Project PEst-OE/EME/UI0667/2011 – UNIDEMI.

REFERENCES


