Proceedings of the 7th International Conference on Mechanics and Materials in Design,
Albufeira/Portugal 11-15 June 2017. Editors J.F. Silva Gomes and S.A. Meguid.
Publ. INEGI/FEUP (2017)

PAPER REF: 6479

SIX SIGMA AND QUALITY GATES: IDENTIFYING THE CRITICAL PATH AND ENSURING CONSISTENT QUALITY OF EXECUTION

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ABSTRACT

This work describes in detail the development of a systematic and standardised Six Sigma approach - outlined in four steps. The first step has the objective of defining the activities and respective goals for each DMAIC phase. Step two focuses on the determination of their required inputs and the thereby generated outputs. Step three involves establishing a chronological order of the activities, integrating the findings of step one and step two. This is determined by identifying the flow of information between activities. The generated outputs of each activity are linked to inputs of dependent activities and vice versa. Once the chronological order is established, the critical path of activities and their respective inputs/outputs can be mapped. In this regard, the critical path formally identifies activities that need to be executed in the given sequence in order to gather all the information required. Following the identification of the critical path, the final step involves its alignment with quality control points, in this context Quality Gates. Predefined hard factors are set to each gate that have to be satisfied in order to move forward on the critical path. Achieved results are examined on quality of execution and completeness and whether the specified conditions are met. Therefore, Quality Gates safeguard that no crucial activity/information is omitted, thus ensuring consistent goal-oriented project evaluation (Cooper, 1990; Hawlitzky, 2002).

Keywords: six sigma approach, critical path, quality gates, DMAIC.

PROBLEM AND THEORY

Six Sigma is a quality management approach that pursues the goal of process improvement and has been implemented for years by successful companies with high demands on quality (Töpfer, 2016). The aim of the approach is the reduction of ubiquitous variations and thus the realisation of defect-free processes and accompanying defect-free products and services, as well as the reduction of quality costs (Jochem, 2015; Töpfer, 2016). Depending on the framework requirements of the given problem, Six Sigma provides several problem solving procedures for the solution of the respective problem. This work focuses on project-based process improvement of existing processes, products and services.

With regard to existing processes, products and services, the Six Sigma approach makes use of the DMAIC cycle, a structured problem solving procedure, implemented to transform an unsatisfactory actual state into a desired state, the latter signifying the fulfilment of a desired requirement (Herrmann, 2011). Within Quality Science, together with the Deming cycle (Plan-Do-Check-Act), the DMAIC problem solving procedure represents one of the most prominent approaches for project-based continuous improvement. Its name is an acronym for the phases of the problem solving procedure: Define, Measure, Analyse, Improve and

Control. Within each phase several goal-oriented activities (or techniques, methods and instruments) from the fields of quality, process and project management are implemented in order to provide the phase-specific content, see table below (Herrmann, 2011; Jochem, 2015). The phase-specific contents can also be interpreted as sought-after targets.

Table 1 - Phases and respective content of the DMAIC cycle

Phase	**Content**
Define	Understand the problem and its impact
Measure	Develop and carry out a measuring concept appropriate to the problem
Analyse	Identify the problem's primary causes of variation
Improve	Develop suitable solutions for the problem causes and prepare their implementation
Control	Implement the solutions and secure long term success

With regard to the chronology of the phases as well as to their content, the DMAIC cycle provides a structured generic guideline as to how to reduce variation for any existing process. However, this sequential way of proceeding describes a universal, yet abstract approach as it broadly specifies the execution within each phase (Mast, 2012; Jochem, 2015). For example, with regard to the Define phase's content, some authors suggest the implementation of a process analysis on a meta level in order to help understand the problem and its impact (Jochem 2015; Wappis, 2013; Pande 2000). Other authors, however, suggest the process analysis be implemented as part of the Measure phase in order to help develop a measuring concept appropriate to the problem (Kubiak, 2009).

Due to the generic characterisation of activities the actual roadmap and its activities can be diversely combined and implemented. Therefore the specific activities and their logical relations are not explicitly defined and do not underlie a predefined logic nor order. This is widely recognisable throughout the DMAIC-related literature. Depending on the author, the implemented activities viewed as necessary in order to achieve the phase-specific content as well as their chronological order may differ. Hence, the choice of activities and their sequence within the DMAIC phases, are to great extent shaped by the individuality and subjectivity of the user. Accordingly, pertinent literature and present practice attest the non-existence of a standardised procedure in terms of DMAIC-related activities (Tjahjono, 2010).

Furthermore, only few authors incorporate a consistent project evaluation concept that controls quality of execution throughout the DMAIC phases. In general, most authors suggest the use checklists at the end of each phase in order to examine predefined objectives for completeness (Pande, 2000; Kaufmann, 2012; Jochem, 2015). Pande even provides standard checklists with basic instructions for key activities.

According to Meran, reviews can be held in order to present and assess achieved results and new findings (Meran, 2012). A review is held at the end of a DMAIC phase in order to present achieved results, the procedure of their generation as well as new findings. The achievement of set objectives is assessed based upon the presented information. If all objectives are met, the project is to be continued into the next phase. If not all are met, further steps have to be discussed to ensure that all prerequisites for the continuation of the project are fulfilled (Meran, 2012).

As described, in both forms of evaluation, the achievement of the phase's objectives is examined based on the presented information. However, both forms of evaluation are generally conducted at the end of each DMAIC phase that poses a severe shortcoming. Incomplete and/or flawed information is discovered at a very late stage of a phase. Failure to consistently control the executed activities and their results increases the risk of poor decision making and ultimately manifests itself in costly as well as resource- and time-consuming implications. Consequently, the Six Sigma approach lacks a consistent quality control concept.

PURPOSE

Overall, the implementation of the Six Sigma approach demands highly qualified users and thus is often assigned to experts in the field of Six Sigma (primarily Master Black Belts and Black Belts). Practical experience and expertise are essential for project-specific decision making, particularly with regard to the above. The predominant implementation by experts highlights the necessity for a standardised approach and consequently the conception of a procedure model in such a way as to enable a broader circle of users (Tjahjono, 2010). Furthermore, a quality control concept is needed to ensure consistent quality of execution.

APPROACH

This work describes in detail the development of a systematic and standardised Six Sigma approach - outlined in four steps, see figure 1.

1. The first step has the objective of breaking down each phase of the DMAIC cycle to a sufficiently granular level of phase-specific activities. The latter are then standardised as well as are their respective goals defined.
2. Step two focuses on the determination of the required inputs of the standardised phase-specific activities as well as their generated outputs. Thereby, the input usage and transformation is examined for each activity in order to help determine the activity's output. In addition, the outputs are consolidated based on the previously defined activity's goal.
3. Step three involves establishing a chronological order of the activities, integrating the findings of step one and step two. This is determined by identifying the flow of information between activities. The generated outputs of each activity are linked to inputs of dependent activities and vice versa. Once the chronological order is established, the critical path of activities and their respective inputs/outputs can be mapped. In this context, the critical path does not identify activities that need to be completed on time in order to complete the project on time. In this regard, time is not the key issue of the critical path analysis. However, the critical path formally identifies activities that need to be executed in the given sequence in order to gather key information required to complete the project. Therefore, each critical activity must generate the desired key output in order to proceed on the path.
4. Following the identification of the critical path, the final step involves its alignment with quality control points, in this context Quality Gates. Predefined hard factors are

set to each gate that have to be satisfied in order to move forward on the critical path. Achieved results are examined on quality of execution and completeness and whether the specified conditions are met. Therefore, Quality Gates safeguard that no crucial activity/information is omitted, thus ensuring consistent goal-oriented project evaluation (Cooper, 1990; Hawlitzky, 2002).

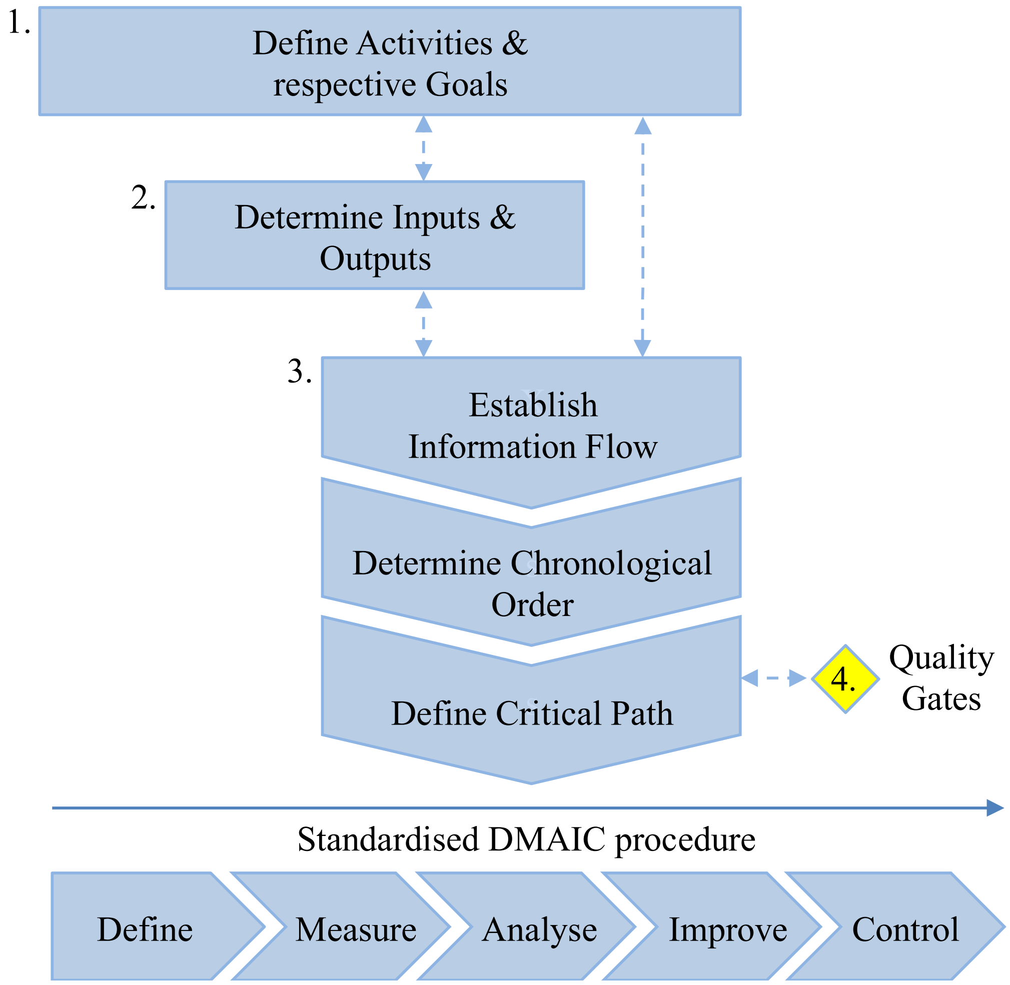

Fig. 1 - Standardising the Six Sigma approach step by step

DEFINITION OF ACTIVITES AND RESPECTIVE GOALS

This work aims to establish a standardised procedure with respect to the DMAIC cycle. Hence, the focus of this work lies on its phase-specific activities. As a first step, a structure for classifying activities is determined, given the fact that certain activities signify a higher role to the fulfilment of a phase's content as others. As a result, each phase is subdivided into two layers. An activity on the superordinate layer can be interpreted as a principal activity, whereas an activity on the subordinate layer describes an auxiliary activity. A principal activity always consists and is dependent of at least one or more auxiliary activities.

Table 2 - Classification of activities, example for Define phase

Phase	Principal Activity	Auxiliary Activity
Define	Define Project	Define Problem
		Determine Project Scope
		…
	Develop high-level Process Map	Identify Core Process and essential Sub-Processes
		Determine Process Inputs and Outputs and Process Participants
		…
…	…	…

The identification of principal and auxiliary activities or activities in general, however, proves to be of major difficulty, as these are generally not laid out as such. In both theory and practice, activities are often combined and implemented as integral parts of techniques, methods or instruments. Users that implement the DMAIC cycle, do so by implementing techniques, methods and instruments. Accordingly, DMAIC-related literature mainly deals with their usage and implementation, leaving little room for visible distinction between single activities. Therefore, the techniques, methods and instruments form the starting point for identifying the phase-specific activities. Table 3 outlines the procedure for their identification and determination.

Table 3 - Identifying and determining the phase-specific activities

Step	Tasks
1	Break down techniques, methods or instruments into distinguishable activities
2	Consolidate and standardise activities
3	Define goal for each activity

BREAK DOWN TECHNIQUES, METHODS AND INSTRUMENTS INTO DISTINGUISHABLE ACTIVITIES

In order to identify the activities, these have to be viewed separately from techniques, methods or instruments. Thus, the bundle of activities embedded within a technique, method or instrument must be broken down into distinguishable activities. As an example, the procedure is described for the technique Project Charter (Define phase). In this regard, there are many options for developing the project document that states the project's mission, benefits and scope (Jochem, 2015; Kubiak, 2009). Its most common elements are Problem Statement, Goal Statement, Project Scope, Project Benefit, Team Members and Resources, Preliminary Project Plan and Project Authorisation (Jochem, 2015; Pande, 2000; Kubiak, 2009; Toutenburg, 2009). The task is to identify the activities embedded in the elements. For example, the element Problem Statement can be transformed into an activity by formulating the activity "Define Problem". Likewise, the element Project Scope can be summarised as the activity "Determine Project Scope". This procedure is implemented for the remaining elements. After having transformed all elements into an activity the technique's task becomes more visible and comprehensive. As a result, the overall activity behind Project Charter can be summarised as "Define Project".

Finally, the identified activities are then classified accordingly for each author, see table 2. With regard to the above, “Define Project” is classified as the principal activity, whereas “Define Project” and “Determine Project Scope” are classified as auxiliary activities. This procedure is implemented for the remaining activities of the viewed phase. As a result, a list of summarised and distinguishable DMAIC-related activities (classified into principal and auxiliary activities) is established for each author.

CONSOLIDATE AND STANDARDISE PHASE-SPECIFIC ACTIVITIES

Depending on the author, the classification of activities may differ so that principal activities may include more or less auxiliary activities than suggested by others. In other words, an auxiliary activity may be assigned to different principal activities, depending on the author. In addition, what one author may classify as an auxiliary activity may be classified as a principle activity by another auther and vice versa. For instance, within the principal activity “Define Project” Kaufmann includes the auxiliary activity “Analyse Stakeholders” (Kaufmann, 2012). As an auxiliary activity it is also classified by Wappis. However, he assigns it to a different principal activity, namely to “Develop high-level Process Map” (Wappis, 2013). Jochem and Kubiak on the other hand, classify “Analyse Stakeholders” as an independent principal activity (Jochem, 2015; Kubiak, 2009).

Furthermore, an activity may be assigned to a different phase, depending on the author. For example, the principle activity “Development of a high-level Process Map” is commonly implemented within the Define phase (Jochem 2015; Wappis, 2013; Pande 2000), whereas Kubiak positions this activity within the Measure phase (Kubiak, 2009). As Kubiak is one of the few advocates who position the activity within the Measure phase, it is determined that it is positioned within the Define phase.

Consequently, great discrepancies can be identified between the lists of activities of the authors, with regard to the classification of principal and auxiliary activities as well as to their phase-specific positioning. The task is to consolidate these activities. Therefore, the lists of activities prepared in the previous step that comprise a maximum yield, are compiled into a single narrowed down list of activities. Thereby, only those activities that are described by the vast majority of authors and that show overlapping and commonalities are taken into account. As a result, the final classification of principal and auxiliary activities as well as their phase-specific position is determined and standardised.

DEFINE THE GOAL FOR EACH ACTIVITY

Once the DMAIC-specific activities are determined, the last step is to determine their respective goals. The goal of an activity is to fulfil a specific purpose, the latter being the generation a specific content, outcome or output. Therefore, if a desired output is needed, the appropriate activity can be identified based on its purpose/goal. In other words, a specific output can be linked to a specific goal and therefore to a specific activity (retrograde approach).

This step is crucial for understanding the implementation of a specific activity. The understanding supports the determination of activities that have to be implemented in order to generate each phase’s content, see table 2. As a result, the standardised activities are complemented by their respective goals.

DETERMINATION OF REQUIRED INPUTS AND GENERATED OUTPUTS FOR EACH ACTIVITY

As described above, the implementation of an activity has the purpose/goal to generate a specific content, outcome or output. This may present itself in form of knowledge, a finding or a complete document of qualitative or quantitative nature. The output is generated through transformation of an input. The latter, also may present itself in form of knowledge, a finding or a final document of qualitative or quantitative nature. As principal activities signify an aggregation of their auxiliary activities, the former do not require an input nor do they generate an output. Therefore, every auxiliary activity consists of one or multiple inputs and at least one or multiple outputs. The aim is to identify the required inputs of every auxiliary activity as well as its generated outputs.

DETERMINATION OF REQUIRED INPUTS

The determination of the required inputs of an auxiliary activity is achieved by gathering all of its eligible inputs. The result is a maximum list of possible entries. These are narrowed down through pairwise comparison to a small number of most significant inputs. The inputs are then categorised as basic requirement, performance requirement or delight requirement. The assigned category signifies the degree of dependence of an input for an activity. Inputs that are categorised as basic requirement are recognised as imperative for the implementation of the viewed activity. Thus, they represent the minimal requirement. On the other hand, inputs that are categorised as performance or delight requirement are not imperative for the implementation of an activity. However, they may to some extent enlarge and ameliorate the generated output. As a result, the standardised activities are complemented by their respective inputs.

Figure 2 shows an example of the auxiliary activity "Identify Core Process & essential Sub-Processes" of the principal activity "Develop high-level Process Map" (Define phase). Its identified inputs are "Problem Statement" and "Project Scope". The former input is considered a performance requirement, whereas the latter is considered a basic and therefore an imperative requirement for the implementation of the auxiliary activity "Identify Core Process & essential Sub-Processes".

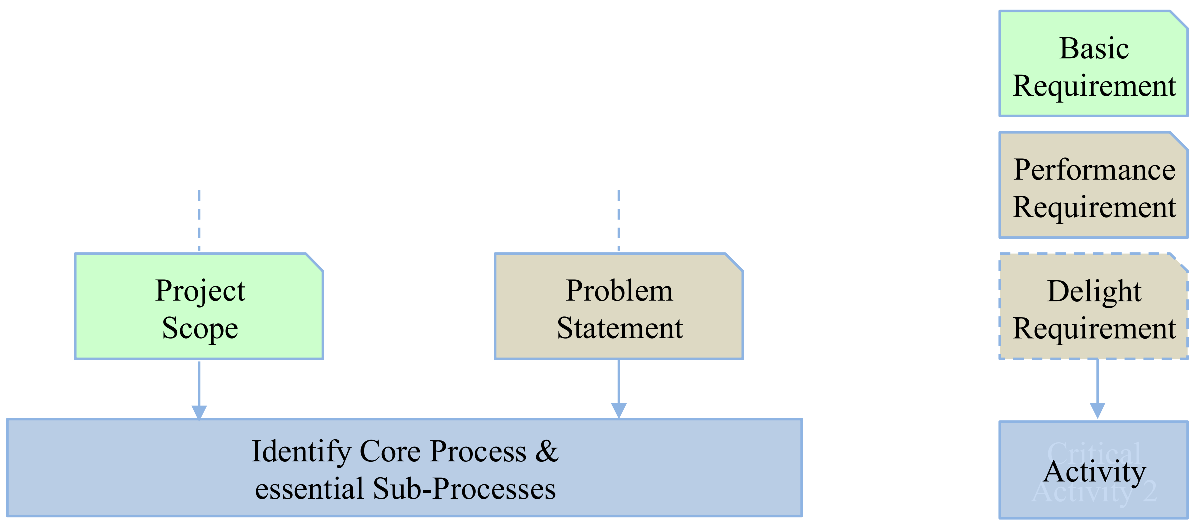

Fig. 2 - Determination and categorisation of required Inputs for the auxiliary activity "Identify Core Process & essential Sub-Processes"

DETERMINATION OF GENERATED OUTPUTS

The determination of an activity's output is achieved by examining the input usage and the transformation process within the auxiliary activity. The essential determinant is the activity's purpose/goal. In general, the activity's goal implies a specific output. Therefore, based on the activity's goal, the output can often be logically deducted (progressive approach). For example, the principal activity "Define Project" includes the auxiliary activity "Define Problem". The latter activity has the purpose/goal to provide a precise explanation of the problem and the reasons why the company is adversely affected or why the current situation has arisen. Based on the activity's goal, the output can be logically deducted. The content of the output must be a description of the problem, thus, the output is a "Problem Statement".

In addition, to consolidate the identification of an activity's output, the linkage between output and goal/activity can be made use of (retrograde approach). The outputs realised by techniques, methods or instruments are broken down into distinguishable units of outputs. Regarding the same example as above, it is known that the "Problem Statement" is an output of the technique "Project Charter". With view to the standardised activities and their respective goals, the output "Problem Statement" can be directly linked to the corresponding goal of the activity "Define Problem". As a result, the standardised activities are complemented by their respective outputs.

ESTABLISHING A STANDARDISED SEQUENCE OF DMAIC-RELATED ACTIVITIES

As stated, pertinent literature shows great discrepancies with respect to the sequence of DMAIC-related activities. For example, within the project's early phase, Pande, Jochem, Kaufmann and Wappis largely regard the principal activities "Define Project", "Develop high-level Process Map" and "Determine Customer Requirements/Critical Quality Features" as essential to obtaining the phase's contents - in that order (Pande, 2000; Jochem, 2015; Kaufmann, 2012; Wappis, 2013). In accordance, Kubiak and Toutenburg regard the same principal activities as essential. However, they outline a different sequence, starting with "Determine Customer Requirements/Critical Quality Features", continuing with "Define Project" and ending with "Develop high-level Process Map" (Kubiak, 2009; Toutenburg, 2009). It is apparent, that the DMAIC cycle lacks a standardised sequence (Tjahjono, 2010).

The task is to determine a standardised sequence of the activities by integrating the findings of step one and step two. So far the phase-specific activities have been identified and standardised. Furthermore, they have been complemented by required and generated information - inputs and outputs. In order to determine a chronological and standardised sequence of activities, the flow of information between activities must be identified.

ESTABLISHING A CHRONOLOGICAL ORDER OF ACTIVITIES

The first step is to establish a connected network of activities by outlining the informational relation between the activities. For this purpose, only auxiliary activities are taken into account as principal activities do not require inputs or generate outputs. The determination of the information flow is achieved by linking the identified outputs generated by activities to inputs of dependant activities and vice versa. An excerpt of the procedure is outlined in figure 1 for the auxiliary activities "Identify Core Process and essential Sub-Processes" and

“Determine Process Inputs and Outputs and Process Participants” of the principal activity “Develop high-level Process Map” (Define phase).

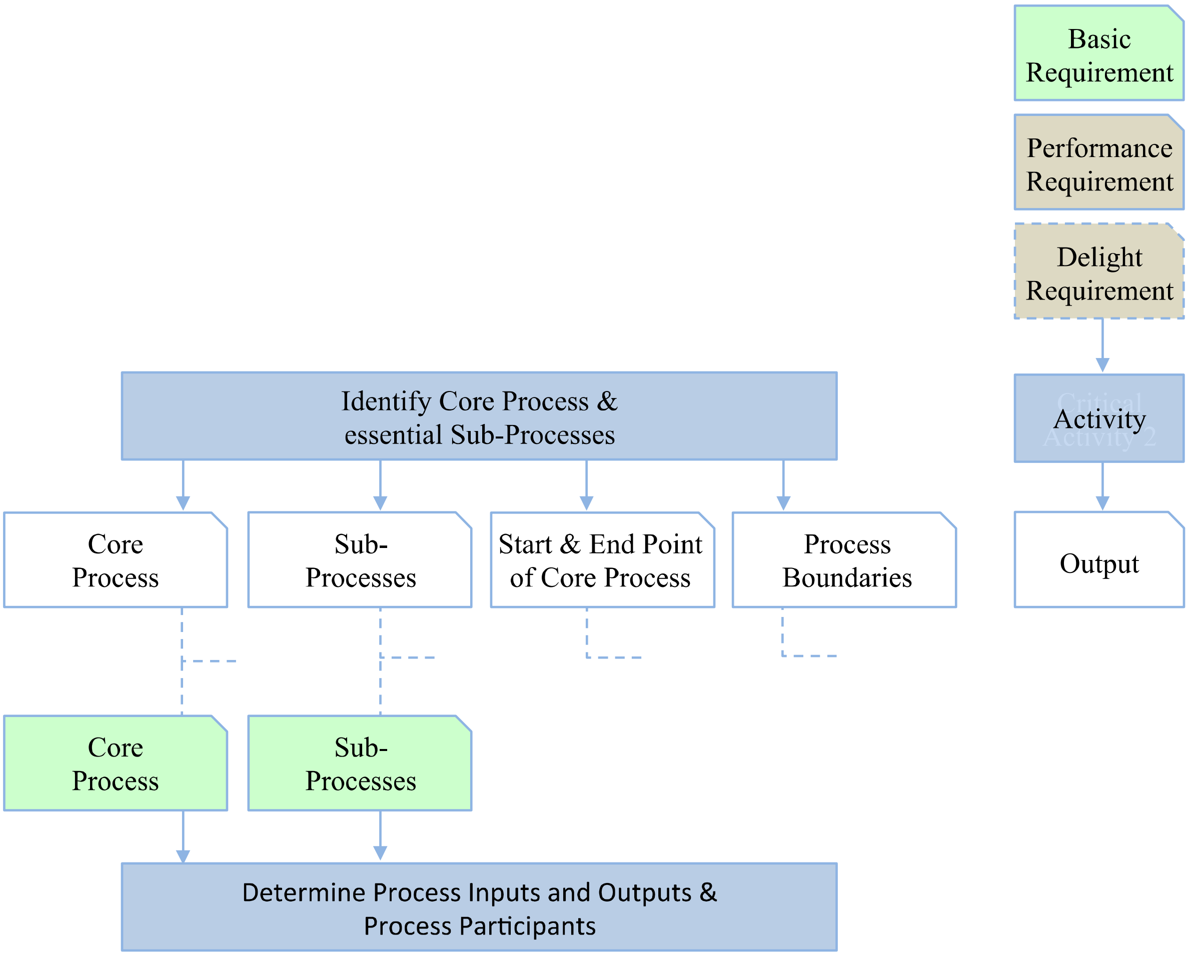

Fig. 3 - Establishing a network of activities by linking outputs of activities to inputs of dependant activities

The procedure is carried out for all DMAIC phases. As a result, a total and coherent network of related activities is mapped. Simultaneously, the predecessor relationships are visualised. Thus, by taking the predecessor relationships into account, the activities can be scheduled according to each activity’s time of completion. As a result, their chronological order is determined.

IDENTIFYING THE CRITICAL PATH OF ACTIVITIES

The critical path analysis formally identifies those activities that need to be completed on time in order to complete the project on time. Thereby, the dependencies as well as start date, duration and end date of each activity are taken into account. As a result, the critical sequence of activities as well as the minimum length of time to complete the project - critical path - is determined.

In this context, however, the emphasis of the critical path does not lie on the time aspect. The emphasis lies on the transfer of critical information or basic requirement outputs that are regarded as essential to implementing the DMAIC cycle and thus, completing the project.

Based on the identified chronological order of activities, the critical path can be determined by focusing on the critical informational dependencies between activities. For that purpose, the network of DMAIC-related activities mapped in the previous step is walked through from back to front. The main emphasis is on the key outputs of activities that are critical for project progression. In other words, activities on the critical path must be implemented in sequence with each activity being completed before subsequent activities can begin. For example, within the Define phase, the auxiliary activity "Determine Project Scope" of the principal activity "Define Project" is imperative for the implementation of the entire principal activity "Develop high-level Process Map". The latter cannot begin until it obtains the input from the activity "Determine Project Scope". Therefore, it signifies a critical activity for project progression and is thus integral part of the critical path. Finally, after analysing the network of DMAIC-related activities from back to front, the critical path of the DMAIC cycle is determined. As a result, the user is enabled to implement the DMAIC cycle and thus, the improvement project, in a systematic and standardised manner.

ALIGNING QUALITY GATES TO THE CRITICAL PATH

As described above, only few authors incorporate a project evaluation concept that consistently controls quality of execution throughout the DMAIC phases. In general, project evaluation is conducted at the end of each phase, thus increasing the risk of detecting incomplete and/or flawed information at a very late stage within a phase. Therefore, a consistent quality control concept is needed in order to ensure consistent quality of activity execution and thus, project success.

For this purpose, significant quality control points within the DMAIC phases are determined. The identified critical path of activities is used as the basis. Each activity on the path represents an imperative element to achieving the project's goal by providing the essentially needed information (basic requirement outputs). Therefore, quality control points are positioned after each critical activity in order to safeguard that all prerequisites are fulfilled and no crucial information/activity has been omitted for the next step (Cooper, 1990; Hawlitzky, 2002). In this context, the quality control points are formed by Quality Gates. A generic critical path with Quality Gates is outlined in figure 4.

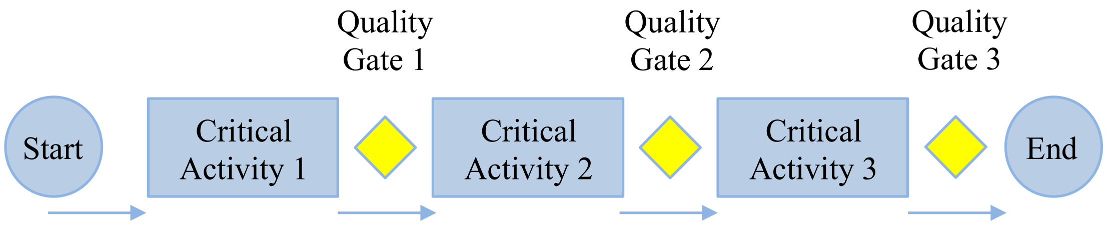

Fig. 4 - Generic critical path aligned with Quality Gates

These have the purpose to evaluate and assess the generated information or output of the respective activity. Each gate is provided with predefined activity-specific hard factors that have to be satisfied in order to move forward on the critical path. For example, as described, the auxiliary activity "Determine Project Scope" of the principal activity "Define Project" is integral part of the critical path. The existence of its output is imperative for proceeding to the principal activity "Develop high-level Process Map". Therefore, a Quality Gate is positioned between the principal activities "Develop high-level Process Map" and "Define Project" in order to control the latter activity's quality of execution, see figure 5. In this regard, the output

“Project Scope” is assessed on completeness and content correctness/accuracy. If all objectives are met, the project is to be continued into the next principal activity “Develop high-level Process Map”. If not, further steps have to be discussed and initiated to ensure that all prerequisites for continuation are fulfilled.

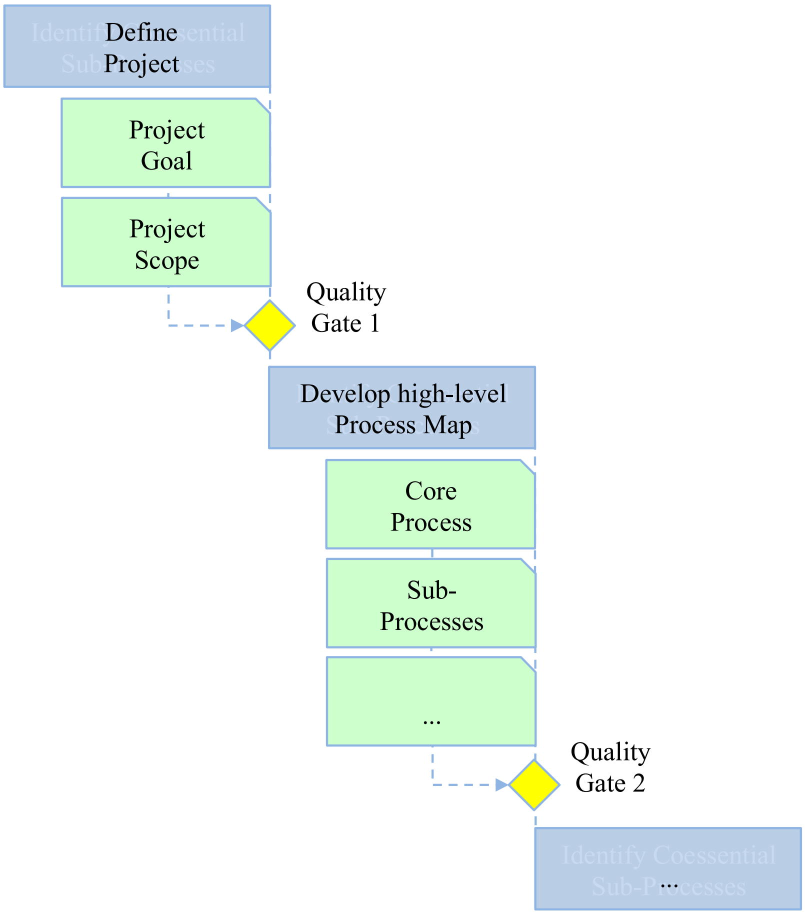

Fig. 5 - Quality Gates positioned between critical activities in order to evaluate and control critical information (basic requirement outputs)

Accordingly, Quality Gates are positioned along the critical path between critical activities. Thereby, each gate is individually designed by including its activities’ critical particularities. As a result, in case of identified incomplete and/or flawed information at a gate, these can be corrected without threatening/initiating subsequent activities. Consequently, quality of execution and thereby, goal-oriented project progression, is consistently controlled and safeguarded.

FINDINGS

The definition of standardised principal and auxiliary activities for each DMAIC phase is essential for laying the foundations of this work. Based on the defined activities, their goals, inputs and outputs can be determined. Consequently, the flow of information between activities can be mapped by linking generated outputs of activities to the inputs of dependant activities. Thereby, the predecessor relationships can be identified, enabling the determination of the chronological order of activities. By emphasising the critical informational dependencies, the critical path of activities is determined. Thus, the sequence of imperative activities/outputs along the DMAIC cycle is outlined. Thereby, the user is enabled to carry out an improvement project in a systematic and standardised manner.

Furthermore, due to the integration of Quality Gates, users can consistently evaluate the effective pursuit of set objectives. The improvement project is not assessed at the end of every phase. Instead, a phase contains several Quality Gates that are positioned between critical activities. These ensure consistent that no incomplete and/or flawed information is passed onto the subsequent activity, thus safeguarding goal-oriented project progression and success. Consequently, the DMAIC cycle, and in this context, the Six Sigma approach, comprises a consistent quality control concept.

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