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Procedia CIRP 17 (2014) 32 – 37

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Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Application of the stage gate model in production supporting quality management

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Abstract

Product and process quality was and still is a key factor of success for manufacturing companies in the competitive global business environment. The stage gate model represents a well-established method for quality management in the product development domain. This paper discusses the application of the stage gate model in the domain of production. The two domains differ in certain areas, which has to be reflected by the adapted stage gate model. The preliminary findings of the two case studies, covering manufacturing and assembly processes, indicate that an adapted stage gate model may provide valuable support for product and process quality improvement. However, the success is strongly dependent of the right adaptation, taking the individual requirements, limitations and boundaries into consideration.

Selection and peer-review under responsibility of the International Scientific Committee of “The 47th CIRP Conference on Manufacturing Systems” in the person of the Conference Chair Professor Hoda ElMaraghy”

Keywords: stage gate model; quality gates; manufacturing systems; product state; data capturing; quality management; relevant information

1. Introduction

Manufacturing systems are becoming increasingly complex and with this development the challenges towards information management increase. With each step along the manufacturing programme, the potential costs of quality problems namely rework or scrap increase. Today, the technological development, especially in sensor technology, allows for measuring a large amount of data during the manufacturing process. Common tools utilized in intelligent manufacturing systems like process monitoring, diagnostics and control, made large progress in order to handle quality problems. Most of those models rely on the availability of relevant information and data of the product state along the process at the right time (use of data). There is a lot of research available on when the relevant information must be available during a production process. However, determining the right time (capturing of data) within the process to capture the relevant information is not yet sufficiently discussed by industry and academia.

The stage gate model [1, 2] presents a well-established methodology to determine so called gates during a product and software development process, at which the state of a development process is matched against agreed parameters. In case the state does not match, the process cannot continue. Even though characteristics and requirements of production differ from product development, the question arises if applying such a model in that domain could be beneficial from a (product) quality perspective. Questions such as the ones listed below are analyzed in the following sections (see [Q1-Q4] in the text to navigate directly to related discussion):

- [Q1] Is the stage gate model transferable to the production / manufacturing domain?

Selection and peer-review under responsibility of the International Scientific Committee of “The 47th CIRP Conference on Manufacturing Systems” in the person of the Conference Chair Professor Hoda ElMaraghy”
doi:10.1016/j.procir.2014.01.071

- [Q2] What are the potential benefits of applying this model in manufacturing?
- [Q3] Does the model have to be adapted and if yes, what has to be adapted and why?
- [Q4] What are challenges & limitations?

1.1. Structure of paper

The paper first presents the state of the art in information capturing in manufacturing with a focus on determination of the right timing, before introducing the stage gate model [1, 2]. The "suitability" of the stage gate model from the product development domain in production is elaborated based on a comparison of manufacturing processes and software/product development processes. Then, to preliminary evaluate the theoretical findings, two case studies, one from a SME with job-shop manufacturing and a second one from a clocked assembly line at an automotive OEM, will be presented with an application of the model. A critical discussion will conclude the preliminary findings, followed by an outlook on future research.

2. Background

In this section, after briefly establishing the perspective on information capturing as a basis for the further discussion within this paper and introducing the original stage gate model from the product development domain, a comparison of production and development processes is presented. The findings of this comparison are the basis for the later application of a product development support method, the stage gate model, in a production environment.

2.1. Information capturing in manufacturing

From an item-level Product Lifecycle Management (PLM) perspective it is necessary to link the captured information to a specific object. Therefore, the object has to be identified precisely and uniquely. The identification can take place automatically by e.g., scanning a barcode or a RFID transponder or by entering the information manually into an IT system etc. Another critical element of information captured is time. A time stamp integrated into every event captured is necessary for having unique information. Moreover, the time stamp is necessary to have a precise history of every object being tracked within the supply chain. Knowing about the location of an object is also very important when generating an event, e.g. information of the current process can be derived based on location/time. Last but not least, the product state, which incorporates various characteristics of a product e.g., quality, dimensions, etc. of an object is considered relevant information. Based on the product state's characteristics, the following process steps and their parameters within supply chains can be planned. An example for a state characteristic is the diameter after machining, but also residual stress allocation within a steel disc [3]. In this context, the question of the time horizon of information capturing comes up. As stated before, the information and data has to be captured in real time, which is understood within this work as available when needed.

2.2. Stage gate model

The stage gate model with its deployment of quality gates is applied primarily in product development processes. The first occurrence was in the software development domain [4]. The development of complex products often carried out over a period of several years, leads to significant challenges when it comes to coordination and synchronization. It is elementary to agree on a reference process, which guides the development teams through the process. The development tasks are structured in consecutive process phases based on the reference process and distinguished by quality gates as a monitor and control tool [5]. The basic idea of the stage gate model is to divide a process in different phases and create a quality gate at critical points in order to secure that the targeted goals are reached before proceeding to the next process phase [6]. The quality gates represent decision points, which determine on the basis of the current status of the process if the project is continued, adapted/revised or terminated [7]. The development process cannot pass a gate when it does not meet all set criteria [1].

The phases of a product development process are difficult to plan, especially the early ones often inheriting creative parts and parts without clearly defined goals. For these phases, the stage gate model offers the advantage to create a monitoring and control mechanism without set in stone timeframes and the needed flexibility solely based on the state of the project [8]. The method is especially useful when the successful launch of a (later) process phase depends on the fulfillment of all requirements by previous processes [2, 6].

Today the stage gate model is applied in practice in various industries supporting product development processes. In the automotive industry, BMW, Audi, General Motors and Daimler are examples of companies successfully implementing the stage gate model. In practical application different variations of the term stage gate were established. It was Daimler who introduced the most well known variation naming the gates 'quality gates' [5].

Even though quality gates share various characteristics with milestones, quality gates and milestones are not the same. Quality gates determine distinct checkpoints where specifically defined requirements are reviewed in a coordinated effort between process customer and process supplier. The accomplished results needed and how they have to be measured (e.g., through Key Performance Indicators (KPIs)) are described in detail in the checklists for the quality gates. For milestones it is not necessary to define specific KPIs. Milestones incorporate mainly the definition of target dates for the accomplishment of certain targets. A milestone can therefore be 'passed' without reaching the defined target, whereas that is not possible for a quality gate [6]. For quality gates, result oriented product and process specific content and performance has to be defined and monitored [9].

The goal of quality gates is the improvement of process quality and thereby ultimately of the final product quality through monitoring and control of the product development process. Quality gates are supposed to support the identification of errors and potential errors and their sustainable termination at an early stage [10].

Furthermore, quality gates are supposed to reduce cost and time of a product development process and the risk of the process running in an unwanted direction [2]. The results of every project phase are matched to the target requirements of all relevant stakeholders. This allows reacting to discrepancies at an early stage, which is especially helpful as cost driving quality deficiencies have their origin in the early planning and organizational phases of the development process [6]. The earlier a potential error or a desired change is identified; the cheaper (time/money) is the execution of appropriate measures.

In case of a product development process going completely out of control, making a termination and/or re-launch necessary, an as early as possible determination of issues may also save considerable amounts of time/money [5]. It is therefore advised to place quality gates before phases with high impact, e.g., before acquisition of production equipment. The positioning of the gates is of highest importance.

The stage gate model supports cooperation, collaboration and communication in between stakeholders of a project. Quality gates provide a structure for all partners involved and force stakeholders to regular coordination and communication about the targets and the status quo of the project [2, 11].

2.3. Comparing product development & production processes

Product development and production are both carried out in form of processes, which are characterized by the interaction of humans, material, resources/utilities and information [9]. The basic principles being of similar nature is the foundation of the presented research.

However, there are certain distinct differences between the two domains which will be elaborated in the following. Production processes are mostly recurring processes whereas development processes present unique or at least first-time processes for an entity [12]. The results of a development process are comparably hard to plan from the beginning of the process, which renders the definition of checklist content difficult [13]. Production, with recurring processes, allows for a more detailed definition and continuous update of checklist content through e.g., implementations of feedback loops. As a requirement for the application of the stage gate method in production, criteria have to be defined on how detailed the checklist content shall be and when it may be updated. The failure to meet criteria in production with recurring processes (frequency) leads to another important issue, the need for identification of causes for failure (process analysis) as it effects the efficiency of future production.

The information transfer differs also when it comes to the complexity of the to be transferred content. In a production environment, distinct and rather well defined instructions with little room for interpretations occur on the shop floor level targeting the blue-collar workers [14, 15]. Whereas in development processes, the information transferred, aside from standardised data sets, varies in complexity/content. This aspect has to be reflected in the application of the method.

Production processes, especially a clocked assembly line and batch production, are linked through a variety of direct (inter-)relations. Down time of a process has a direct influence on the following processes [16, 17]. Application of quality gates as originally described in the stage gate model [2] may be problematic in the production domain. The response time in mass production is significantly lower than in development processes [10]. A requirement towards the application must be to integrate the quality gates without causing additional down time. The requirements of the individual production process have to be reflected within the content of the checklist. It may be considered that it is more difficult to apply the method in exiting production lines compared to newly planned and set up ones.

One of the main rules of the stage gate model is that if the process does not meet the set criteria at the gate, it cannot proceed further until the criteria are met. In product development, in such a case, measures to be taken are discussed [6]. In a production environment, this rule has to be adapted due to the low response time in order not to clog the whole production line. It is important to understand that the state of a product in a manufacturing programme may be changed during later processes to meet the criteria of the gate if the problem is identified and communicated to the right addressee. Therefore, in production, a product not meeting the criteria at the gate can still proceed under certain, distinctly defined circumstances. In case study 2, a real life example of such an occurrence is presented.

Other than within a product development process, in production, often multiple products or product variations are manufactured and/or assembled. These different products / product variants can inherit different vulnerabilities and main areas of error [18]. This has to be taken into consideration and be reflected in the checklist development. Multiple checklists or variations of checklists may be necessary.

In the following table (see Table 1) the main points of this section are summarized before the application of the stage gate model in production is elaborated further in the next section.

Table 1. Comparison of product development and production processes

Focus area	Development	Production
basic principles	processes, characterized by interaction of humans, material, resources/utilities and information	processes, characterized by interaction of humans, material, resources/utilities and information
frequency	unique / first-time process	recurring processes
information transfer	variations in complexity and content	distinct, well defined structure
response time	higher response time acceptable	strong focus on low response time
failure to meet criteria	stop – detailed elaboration of next steps (gate not crossed)	gate may be crossed under certain conditions – other-wise mark / phase out product (preferred no full stop)
variations	one process	Different products, product variations

3. Application of stage gate model in manufacturing

The stage gate model's application in a production environment is discussed in the following. First, selected theoretical aspects, which have to be taken into consideration, are elaborated in the first sub-section. Following, two case studies, one located in a manufacturing domain and a second one in the assembly domain are presented in order to preliminary evaluate the theoretical transformation approach.

3.1. Theoretical application of stage gate model [Q3]

For the application of the stage gate model in production, two topics have to be considered: positioning of the gates and content of the checklists.

The *positioning of the quality gates* in the production process determines the results and impact of the application to a large extent. It has to be noted that there is no detailed and generally applicable method of the positioning of the gates. Each production process is individual and thus has different requirements. The selected case studies present two different scenarios within the production domain, a manufacturing process and an assembly process incorporating different organizational types (clocked assembly and job-shop manufacturing). However, there are some universal suggestions that may support the positioning.

As mentioned in the previous section, a gate should be positioned before certain process phases which involve high investments and/or that depend on previous process results. In production, these principles may be transferred to following events with a possible impact on the gate positioning decision:

- *transfer of liability*: e.g., between business units
- *(inter-)relations of processes*: e.g., following process depends on certain product state
- *added value*: e.g., expensive complex milling process based on results of previous processes
- *known failure*: e.g., after a failure prone phase
- *identification of failure*: identification of failure source within the process
- *accessibility*: e.g., check before part is hard to reach due to following processing
- *measurability*: e.g., certain characteristic can only be measured (economically) at certain point
- *process layout*: e.g., for already established processes, where is it possible to put a gate (needed time, space, etc.)

The previous presented events are just a selection and can occur in combination during a production process. However, the number of quality gates is always a trade off, as each gate involves an investment of sort e.g., time and therefore the rule of thumb may be as many as necessary and as little as possible. Some gates, e.g., positioned to identify a failure source can also be temporary. As soon as the failure source is identified and a solution found, the gate is obsolete. It has to be kept in mind that gate positions are to be continuously evaluated and adjusted based on e.g., newly acquired knowledge, changing process requirements or adjustments [4].

As determined by [10], quality gates are used to synchronize the customer performance expectations and the performance capacity of the supplier. Based on this, certain fundamental aspects have to be checked at the gate and may serve as a basis for the checklist content. The decision of the *checklist content* has to be made jointly with the determination of gate positioning, as they may be interdependent to each other to a certain extent. The determination of the checklist content is complex. Various factors have to be considered. A major factor is the customer requirements towards product quality with 'customer' also including internal customers [19]. One approach is that the process owner of the process previous to a gate is responsible for determining the checklist content as it can be assumed that he knows about the target product state after the process. Overall, the system perspective of the product state concept and its description of a product based on a set of relevant state characteristics [20] may provide a supporting framework for the determination of appropriate checklist content for the application of the stage gate model in production.

After the first draft of the checklist content is derived, it is suggested to consult external experts to critically evaluate the content with regard to the process requirements. Personnel, which are directly involved in the processes, may lack objectivity, which reflects on the chosen checklist content [21, 22]. A coordination of the external experts with the process owners may ease that issue and create more sustainable results.

In accordance to the already mentioned possibility of eliminating a gate when a new solution for a failure source is found, it is possible to add or delete certain aspects from a checklist depending on various factors (e.g., failure rate, change of requirements). It is advised to establish an "update process", with a focus on keeping the checklist content in synch with the current process, its requirements and the customer expectations. Another important aspect is the management of product variants with regard to the checklist content that has to be actively taken into account.

3.2. Case studies

Two case studies are briefly introduced, highlighting certain aspects of the previously presented theoretical application. It has to be noted that the determination of the checklist content of the case studies will not be addressed in detail due to page restrictions within this publication.

The application field of the first case study is a manufacturing SME first-tier supplier for an automotive OEM. The production takes place by employing ten turning, eight milling and two balancing machines in a job-shop manufacturing arrangement. The three major processes are carried out fully automated with little chance to interfere.

An existing problem within the operations of the company is e.g., that defective parts are passed through the complete manufacturing programme (see Fig. 1) even though the defect occurs at an early stage rendering following value adding processes obsolete. At the same time, the sources of the defects as well as the causes for the failure to meet the requirements are unknown.

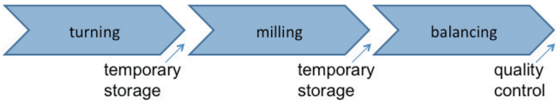

Fig. 1. Case study 1 – manufacturing programme

The major goal of the application of the stage gate model in this company is the identification of the causes for failure within the manufacturing programme. As soon as the causes are known, the company can adapt their processes and ideally terminate the cause or at least reduce its likelihood to reoccur.

As this company produces in a job-shop array with temporary storage between all major processes, the determination of the quality gate positioning takes advantage of the existing down times during the temporary storage by positioning the gates within the gaps (see Fig. 2).

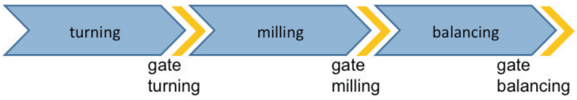

Fig. 2. Case study 1 – quality gate positioning

Case study 2 takes place in a clocked assembly line production of an automotive OEM. In order to reduce complexity, this example will focus on one distinct process instead of looking at the complete production programme. The process in this case study is the installation of the central car wire harness, which involves multiple 'little' individual operations. Within this process, the number of variations of products is considerably high.

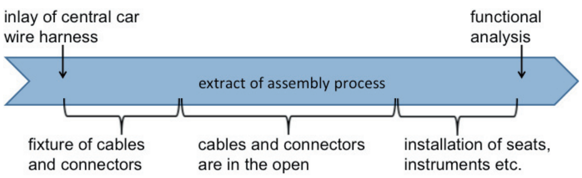

Fig. 3. Case study 2 – assembly process

Existing problems are e.g., defective cables and connectors, which involve high cost for rework in case the defective part is covered/hidden due to following assembly processes (see Fig. 3).

Fig. 3 shows the extract of the assembly line where the cables and connectors are attached to the body. Whereas the cars and cables/connectors vary, the process itself is comparable. The cables and connectors are attached before the seats and instruments are embedded. The functional analysis of the incorporated parts takes place after the seats/instruments are embedded. In case a cable/connector defect is detected, the correction activities demand for a removal of seats/instruments. This is rather complicated and cannot be done directly on the assembly line due to time restrictions (down time leads to high cost).

The position of the quality gate in this case was chosen to be after the implementations of the cables and connecters and the most failure prone part of the process (see Fig. 4).

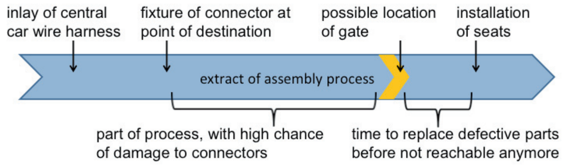

Fig. 4. Case study 2 – positioning of gate

Additionally, an extra timeslot for potential repair activities in case of a detected defect is planned for after the quality gate. This timeslot allows repairing defects before the seats and instruments are incorporated, thus reducing the needed repair time and effort. This is also an example where 'defective' parts can cross a quality gate if it ensured that the defect can and will be terminated by the time of the next process phase with (inter-)relations.

4. Discussion of results

In this section, the preliminary evaluation results of the application of the stage gate model in production are briefly discussed and limitations of the approach presented.

4.1. Discussion

The application of the stage gate model in two different domains of production (manufacturing and assembly) and two different organizational structures (job-shop and clocked assembly line) indicate a broad application field.

In the first case study, the implementation of quality gates between the major processes allows to identify faulty products early in the process and prevent further value adding processes. Failure to comply with the agreed requirements (checklist) of the gate results in either phase out (no additional value add) or rework (adjustment of process). As this happens early in the process, the company is able to save cost according to the 'empirical rule of 10' [6], which states that the cost of removing a defect increases by the factor 10 from one stage to the next. Furthermore, the method forced the company to manage their stock in between processes better. Before, the work pieces were stored wherever there was space. By applying the method, the workers were forced to utilize a more transparent and organized approach. The company considered this side effect very helpful.

The second case study shows how the stage gate model may support detecting defects and react accordingly before the removal of the defect becomes complicated and expensive (money, time and effort) for the company. This additional 'probation' timeslot was received as very beneficial by workers and supervisors as it helped to assure product quality and reduced downtime. Both applications succeeded to support a knowledge creation when it comes to narrowing down sources of defect and thus support transparency and allow the creation of sustainable solutions.

4.2. Limitations & Challenges [Q4]

Even though the preliminary results of the application within the two case studies indicate that the process quality could be increased, the stage gate model is not a perfect solution for every faulty process. The application requires an in-depth understanding of the product, process and (inter-)relations as well as the requirements of the different stakeholders e.g., customers and suppliers. However, the process of acquiring this knowledge about the own operations towards the application of the stage gate model may already be seen as an important result. Another limitation is that whereas the model seems suitable for productions with sufficient batch sizes in order to allow continuous update processes and learning, the benefit for small batch productions has to be investigated.

5. Conclusion and outlook

In conclusion, the preliminary results derived from the two case studies indicate that the application of the product development tool 'stage gate model' in an adapted form in production is beneficial under certain circumstances [Q1]. Quality gates allow companies to avoid unnecessary investment in faulty product and rework and support the identification of causes of defect along the production [Q2].

In the near future, the authors plan to research the application in additional production environments. Furthermore, a combination of the model with state of the art technology like e.g., fully automated gates or enhanced by augmented reality tools will be explored in order to look into 'virtual quality gates', expanding the area of application.

It is planed to develop the presented preliminary into a journal publication with additional focus on the theoretical application. Furthermore, the conducted case studies will be described in greater detail also highlighting aspects concerning the determination of checklist content for the two examples. Additionally, the evaluation will be extended by including further findings and feedback as well as comparing the results of the presented method with results of established QM methods. A combination of the stage gate model and the 'product state concept' concerning checklist content will be explained in greater detail in the planed publication.

Acknowledgements

This work was partly funded by the German Academic Exchange Service (DAAD) through a Ph.D. fellowship (Jahresstipendium für Doktoranden). The authors gratefully acknowledge the support of the DAAD. The results presented are partly based on a Master Thesis of Dennis Zeglin at the University of Bremen. Finally, the authors would like to thank the reviewers for their comments that helped to improve the manuscript.

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