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Production – as seen from product development: A theoretical review of how established product development process models address the production system

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Abstract

It is a well-known fact that collaboration between design and production during product development is a critical success factor. Literature on product development have described many different product development processes (PDP), but engineering students are in general only taught one or a few of the existing models. Given this, it is interesting to investigate how established (and often used) PDP models address production and the development of the production system, since this could influence the presumptions of engineers in industry as well as academic researchers (who in general have been engineering students before pursuing an academic career). In this paper, the authors have reviewed seven established and commonly used (in mechanical engineering education and/or research) PDP models, with respect to how the models address the production system and its development. The models are reviewed with respect to what the PDP model describe as the content of the PDP, inclusion of the development of the production system in the model, the presentation of support tools for production related activities, the level of references or mentioning of production system development theories, the visibility of data transfer needs between product and production system development and the strategic role of production in product development. This analysis shows that production system development is mentioned less in more recent literature but is generally scarcely described. Design for manufacturing and design for assembly tools have been added to more recent literature, which might be a way of managing the decreased inclusion of production system development. Finally, an outline for future research efforts on the topic is presented.
Keywords: Product development processes, Production development, Integrated product and production development, Engineering design, New product development

1 Introduction

Bringing new products to the market faster than competitors is a core success factor for product-producing companies (Zirger & Hartley, 1996). With increased demands on product functionality, cost and sustainability, the demands on the processes used for bringing new

products to market has also increased along with the demands on collaboration and communication between product and production system development functions (Henriksson & Johansen, 2016). In fact, the importance of both DFM (Design for Manufacture) principles as well as teamwork and integration of the manufacturing discipline into product development has been in great focus since the 1980s (Herbertsson, 1999). Different tools for DFM and concepts like Integrated Product Development and Concurrent Engineering has been developed and used a lot since the 1990s which underline the importance of incorporating production issues during product development. A question though is how well we teach this to our engineering students?

Many different theoretical processes for bringing products to market exist e.g. (Andreasen & Hein, 1986; Cooper, 1990; Miller, 1993; Susman, 1992; Prasad, 1996; Cross, 2003; Voland, 1999; Ullman, 2010; Ulrich & Eppinger, 2012; Johannesson, Persson, & Pettersson, 2013), and are used to teach product development to engineering students. While most Scandinavian mechanical engineering students are taught product development, most are only taught one product development process model. Thus, it is of interest to review what a set of well-known product development process models used in engineering education covers in terms of production system development. These product development processes will probably influence the students' view on the collaboration between product development and production system development. When these students later graduate and move on into industry or pursue an academic career and work with research on product development or production system development, this can affect how these individuals work and thus influence development time and cost for the realization of new products.

2 Research questions

The research questions proposed for this study were:

RQ1: How is the relationship between product development and production system development described in literature commonly used in product development education?

RQ2: To what extent is integrated product and production development described in literature commonly used in product development education?

RQ3: Can any historical trends in the description of production system development in product development literature be found?

3 Methodology for the literature review

3.1 Basic approach

To answer the research questions seven different product development process models (PDP-models) were first selected for analysis. A set of seven items of analysis was then defined (see 3.3 below) and each PDP-model was analysed with respect to these. The items represent what are considered as important aspects of Production System Development (PSD) during product development. For six of these items a scale for measuring to which grade the analysed PDP-model supported this item was also pre-defined.

Each PDP-model was then analysed, and the result was summarized in a matrix for side by side comparison.

3.2 Selection of Product Development Process Models

At first, it was decided to analyse a set of PDP-models that are well known, widely used in engineering education and often referenced in research. At least three of these models are presented in textbooks commonly used at Swedish universities as a basic literature about product development. These four models are presented in the following sources:
(Pahl, Beitz, Feldhusen, & Grote, 2007; Ullman, 2010; Ulrich & Eppinger, 2012; Johannesson, Persson, & Pettersson, 2013)
Since research question 3 aimed at identifying any trends in literature presenting PDP-models it was also decided to analyse three older sources:
(Andreasen & Hein, 1986; Cooper R. G., 1990; Prasad, 1996)
Andreasen and Hein (1986) was chosen because it is one of the oldest descriptions of the concept of Integrated Product Development (IPD) (originally presented by Olsson (1985)). One of the corner stones of IPD was to incorporate the production system development during product design to avoid working sequentially.
Cooper (1990) was selected because it introduced the widely used stage gate model of product development; a model that has been widely applied in industry and in research. The original model has been addended by the author (Cooper, 2014) along with co-authors (Cooper & Sommer, 2016), and these have been partially included in the study.
Finally, Prasad (1996) represents one of the most widely used and referenced models that introduced the Concurrent Engineering (CE) concept for product development.
The authors don't believe any of these latter three sources however are currently used as textbooks for engineering students.

3.3 Items of analysis

As mentioned above 7 different items of analysis were developed for this study:

- PD Model Coverage
- Inclusion of PSD (Production System Development)
- Support of PSD
- Support Tools Described
- Reference Degree
- PD – PSD Data Transfer Visibility
- Strategic Role of production in PD

In the following these seven items of analysis are described in more detail.

3.3.1 PD Model Coverage (Horizontal coverage)

The horizontal coverage of the PD process defines the framework for what the PD process actually can contain. Where the PD starts and ends. For instance, a more comprehensive model may include strategic product planning while a less comprehensive model may start directly with concept development. A more complete model also includes later stages that often includes manufacturing related activities. This will probably have impact of how much PSD related activities that can be included since it is likely that a model with large coverage will include more production activities.
As a base model for the horizontal coverage the model in figure 1 below was used. This model is based on a model earlier used by Vinnova (Sweden's Innovation Agency) to describe an entire product life cycle.

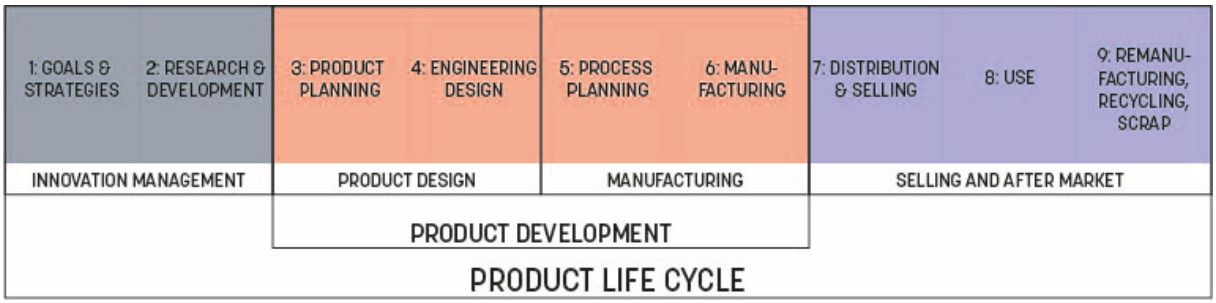

Figure 1. Product life cycle as described by Vinnova, the model used for the horizontal model coverage in this study.

The scale used for the analysis was here the number of phases of the base model above that the PDP-model covered.
Scale: Phases covered by number

3.3.2 Inclusion of PSD (Vertical coverage)

This analysis item aimed to measure the vertical coverage, that is, to what degree manufacturing are included in the overall description of the PD-process. Are manufacturing at all mentioned or is it mentioned as key actor in the PD? Here a scale from 0 to 3 is used:
Scale: 0 – not at all mentioned; 1 – a student understands that PSD exists; 2 – a student understands basic activities of PSD and their relation to PD; 3 – the literature can be used by the student to perform PSD as an integrated part of PD

3.3.3 Content of PSD Support

Production System Development can precisely as Product Development be based on methods and tools. This item of analysis therefore aims at measure to what degree such methods and tools are included in the analyzed model. Here a scale from 0 to 3 is used:
Scale: 0 – no methods or tools presented; 1 – a few methods or tools for PSD are briefly described; 2 – a decent set of methods and tools for PSD are described; 3 – complete coverage of the entire PSD process together with tools and methods

3.3.4 Support tools described

This item of analysis directly correlates to the item *Content Support* described above. Which support tools are presented?
Scale: List of tools

3.3.5 Reference degree

Even if PSD is scarcely described in terms of vertical coverage the model or textbook may refer to other sources describing it more depth. Therefore, it is interesting to analyse to what degree this is done. How usable are the reference list of the literature for PSD? Here a scale from 0 to 3 is used:
Scale: 0 – not at all mentioned; 1 – a student can find a few relevant sources; 2 – a student gets a relevant list of sources of PSD; 3 – the literature points out sources that fully enables the student to perform PSD as an integrated part of PD

3.3.6 PD-PSD Data transfer visibility

Even if PD and PSD is performed in an integrated matter, it still to a large degree, represent two separate activities that must be coordinated with respect to information exchange. Does the

PD-model description clearly point out the data/information flow between PD and PSD during PD? Here is also a scale from 0 to 3 is used:
Scale: 0 – No data flow described at all; 1 – Some flow of data and information are described but far from complete; 2 – The information and data flow is described to a large degree; 3 – A complete description of the information and data flow between PD and PSD

3.3.7 Strategic role of production in PD

The final item of analysis concerns how well production is described from a strategic point of view. It is of no doubt that production nowadays must be considered as having a strategic and important role in product development. Even if specific tools, methods and data exchange is missing in the model the authors believe that at least this strategic role should be emphasized to engineering students. How is production mentioned as a strategic factor in product development? Again, a scale from 0 to 3 is used:
Scale: 0 – No mentioning of production from a strategic role; 1 – Production is mentioned but not emphasized as an important strategic factor; 2 – Production is described as a strategic factor in product development; 3 – Production is described as one of the most important strategic factors for product development

4 Comparison matrix of the reviewed process models

The results from the review of product development process models show that there are distinct similarities and differences between the studied theories described (see table 1). The product development coverage all start with the third phase (“product planning”), but there are some differences in where the models end. Ullman (2010) ends after the fourth phase (“engineering design”), while Andreasen & Hein (1986) includes up to the seventh phase (“distribution and selling”). The inclusion of production system development varies from none (Johannesson, Persson, & Pettersson, 2013; Cooper, 1990; Ullman, 2010) to extensive (Andreasen & Hein, 1986). The examined product development processes are more similar in terms of how well support tools for production system development are described, with all models describing few (Pahl, Beitz, Feldhusen, & Grote, 2007; Andreasen & Hein, 1986; Prasad, 1996) or none support tools. While some process models (Ulrich & Eppinger, 2012; Johannesson, Persson, & Pettersson, 2013; Ullman, 2010) are classified as having no presentation of production system development support tools described, these models have descriptions of DFM and Design for Assembly (DFA) from a product development standpoint, giving some sort of support for including production considerations in the product development work. Others (Andreasen & Hein, 1986) mentions several considerations and questions to ask during development, but these checkpoints cannot easily be described as support tools. The product development process models have a low degree of production system development referencing in general, with Prasad (1996) as an exception. The level of visibility in the data transfer between product development and production system development is also low, with only three models (Ulrich & Eppinger, 2012; Pahl, Beitz, Feldhusen, & Grote, 2007; Andreasen & Hein, 1986) displaying even some of the data transfer. Finally, the description of production’s strategic role in product development differs significantly between the models investigated, with some not mentioning production as a strategic factor at all (Johannesson, Persson, & Pettersson, 2013; Cooper, 1990) and some describing production as a core strategic factor (Andreasen & Hein, 1986; Prasad, 1996).

Table 1. Comparison matrix for the studied product development process models.

	Ulrich & Eppinger (2012)	Johannesson, Persson & Pettersson (2013)	Cooper et al	Pahl, Beitz, Feldhuzen & Grote (2007)	Andreasen & Hein (1986)	Prasad (1996)	Ullman (2010)
Product development model coverage	3-6	3-5	3-6	3-5	3-7	3-6	3-4
Inclusion of production system development	●			●	● ● ●	● ●	
Support tools for production system development				●	●	●	
Support tools described	DFM, DFA	DFM, DFA, modularity	-	DFM, DFA, interface design, modularity	-	DFM, DFA, design for manufacturing quality, design for robustness	DFM, DFA
Reference degree	●	●				● ●	
Visibility of data transfer between product development and production system development	●			●	●		
Strategic role of production in product development	●			● ●	● ● ●	● ● ●	●

5 Analysis

In the literature sample used for this review, the level of coverage of integrated product and production development is low. Some of the authors highlights production as having a core strategic role in production development (Andreasen & Hein, Prasad), but the description of data transfer between product development and production system development is very abstract and low fidelity. This means that an integration of the development processes cannot be done with the information provided by the books reviewed.

The low level of data transfer and collaborative development tools for product and production development indicates a view on the production system as either a static entity or a “greenfield” operation. While for example Ulrich and Eppinger (2012) propose production-related activities throughout the product development process, these activities are more suited for identifying constraints and restrictions rather than developing the production system. The production-

related activities also have a linear dependency, meaning that early activities define the possibilities and constraints for later activities.
It appears that the time of writing for the most thorough descriptions of the collaboration between product development and production system development are from the late 1980's and the early 1990's. After this, the degree of reference and inclusion has declined. While some of the later additions are revisions of older books, most have been continuously revised and edited and have recently published new editions.

6 Conclusions

RQ1: How is the relationship between product development and production system development described in literature commonly used in product development education?

Conclusion: The relationship is typically described as a linear delivery of information rather than a collaboration, where the engineering design of the product is finished or near-finished when the design of the production system is started. This is then complemented with an upstream representation of downstream capabilities and restrictions, to reduce the risk of late project cancellation. This is visualized in figure 2.

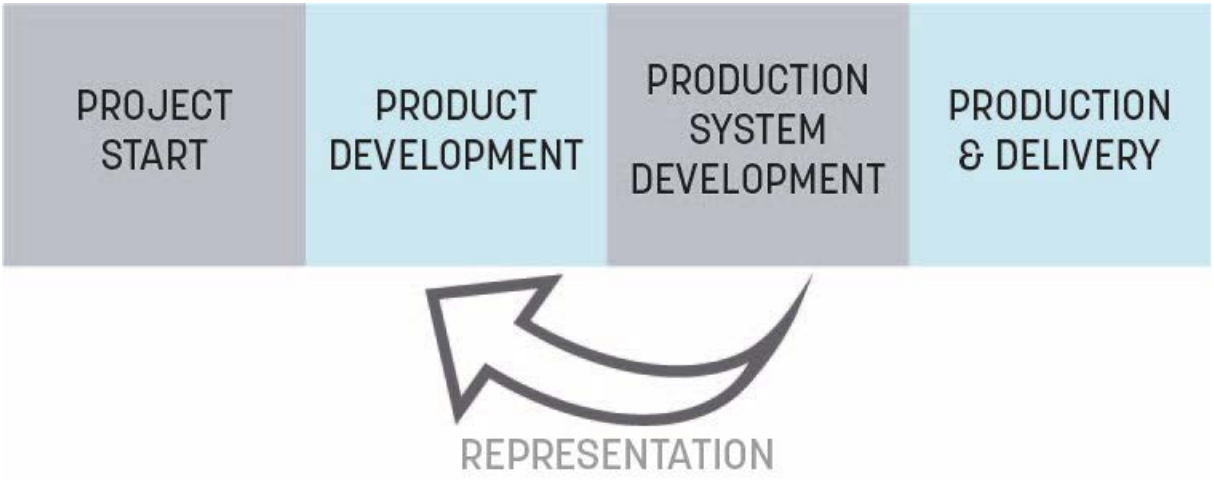

Figure 2. Schematic description of the commonly described relationship between product development and production system development.

RQ2: To what extent is integrated product and production development described in literature commonly used in product development education?

To a very low extent. Andreasen & Hein (1986) have tried to explain an integrated process with product and production system development, but the descriptions of activities are brief or non-existent.

RQ3: Can any trends in the description of production system development in product development literature be found?

Over time, the descriptions of production system development seem to have been reduced in product development literature. DFM and DFA tools have been included in all later revisions of books, with Cooper et al (Cooper, 1990; Cooper, 2014; Cooper & Sommer, 2016; Cooper &

Sommer, 2016) as an outlier not mentioning DFM but instead focusing on for example agile development methods.

7 Discussion and future research

Within the delimitations of this study, the authors find that descriptions of how product and production systems are developed with regards to each other are scarce. If integrated product and production development is a goal for academy and industry, and some sources point to this (Gedell, Michaelis, & Johannesson, 2011; Produktion 2030, n.d.), there seems to be a need to understand the interaction between the product and the production system, and how product design decisions can affect both the performance or robustness of the production system and other possible products made in the same production system. This is not well described in current or historical literature on product development.
Henriksson (2017) has started to describe how the product affects the production system as well as how the production system affects the product, but this needs further investigation in order to propose a methodology for integrated product and production development. This new methodology should also take advantage of the earlier literature and research to generate benefit for both academia and industry, if and when applicable.
A methodology for integrated product and production development should help engineers to for example manage modularization efforts, production flexibility (Gupta & Goyal, 1989; D'Souza & Williams, 2000), product updates and "facelifts" (Andersson, 2016; Henriksson, 2017) as well as giving decision support for whether to select product solutions based on existing production capabilities, or select more suitable product solutions and invest in production technology.

7.1 Possible explanations for low production system development coverage

There are multiple possible explanations for the lower level of production system development inclusion in product development literature.

- Increased usage of engineering projects in education
- Teachers are more aware of production system development (thus it does not need mentioning in the literature)
- Teachers are blind to the lack of coverage of the complexity after having had the books from 1980s-1990s as course literature when studying
- DFM and DFA tools fulfil the need while simplifying the process model
- Reduction of "non-value adding time" between design and production reducing the need
- Redesigned work tasks in industry have eliminated the need for a more complex process model
- The inclusion of production system development is included in courses rather than the literature, to be more easily updated

I the following subsections, these factors will be discussed in detail.

7.1.1 Increased usage of engineering projects in education

The first presented possible factor affecting the coverage of production system development in product development literature; the increased usage of engineering projects in courses, relates to the CDIO initiative of educating engineering students in intrapersonal skills and teamwork when solving technical challenges (Crawley, 2001). In these projects, challenges such as production cost of production constraints can more easily be included to create a learning environment where students can experience the challenge of developing both the product and the production system in an integrated way. It is possible that these changes to the engineering

education curriculum has satisfied the need for inclusion of production system development in product development education, and that the literature has been adapted to fit this change.

7.1.2 Change of teachers' presumptions of the relationship between product development and production system development

The second and third factors are similar but have vastly different effects on product development education. Given that today's teachers and professors probably received their engineering education during the 1980's or 1990's (in some cases early 2000's), they would have taken gotten their education when the collaboration between product development and production system development was most extensively covered in product development literature (Andreasen & Hein, 1986; Prasad, 1996). The could have resulted in two different outcomes: either, the teachers and professors are more aware of the complexity, and therefore emphasize it in education meaning that there is a reduced need for this in literature, or they are blinded by the lack of coverage due to a saturation ("doesn't everybody already know this?") earlier on.

7.1.3 DFM and DFA tools fulfil production development needs

There is also a possibility that the introduction of DFM and DFA tools have, to a satisfying degree, given engineering students enough of an understanding of the production system to reduce the need of including production system development in product development education. This would lead to a simplified model while still reducing development time and cost. This is the fourth presented factor.
DFM and DFA tools are presented in all of the modern product development process models sampled (Pahl, Beitz, Feldhusen, & Grote, 2007; Ullman, 2010; Ulrich & Eppinger, 2012; Johannesson, Persson, & Pettersson, 2013), as well as one of the older models (Prasad, 1996) and is commonly used both in academia and industry.

7.1.4 Reduction in "non-value adding time" between design and production

A possible explanation for the shift in production development focus in literature is that the non-value adding time in industry project has been reduced. Today's organization includes production knowledge earlier in the process, and there is representation from downstream activities in upstream ditto in a structured way to capture information and reduce the risk of early failure in projects. This contrasts the earlier "over-the-wall" principles described by Ullman (2010) with a clear sequencing of tasks and less communication between disciplines, something that might have necessitated a revamp of project organization and product development project methodology.
Modern Product Lifecycle Management (PLM) software may also contribute to "democratize" the information and process in development of new products, since more people can be given access to the actual data. This new software can also contain more information, and more diverse information, than previous media.

7.1.5 Redesigned work tasks in industry

Another reason for these trends could be that the work of the design engineer in industry might have shifted, becoming more constrained by standards and guidelines making sure that components and products being designed are manufacturable rather than having the responsibility placed on each individual design engineer. If such is the case, this could reduce the need of production system development inclusion, since much of the understanding generated from including production system development in early product development stages can be built into standards and guidelines for design engineers.

7.2 Future research

Future research into this topic should examine other product development process models and make a similar review of production system development literature.
Product development process models such as systems engineering (Department of Defense, 2001) have not been fully investigated, and continued work on this topic should cover more product development process models. There is both older literature (such as Hurst (1999)), and newer (not fully implemented in product development literature) product development process models such as Agile Development (Cooper & Sommer, 2016) that could be investigated in order to create a full picture of how production system development is covered in product development literature.
Another future topic is to make a similar review of the production system literature, and how it covers product development. Authors such as Bellgran and Säfsten (2010) have covered the development process of the production system, and a further investigation of how this literature covers the product development process could aid the academic community to understand how the interaction between product and production development is described.
In the long the authors would like to see literature that in depth describes the production system development as a part of product development.

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