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Coordinated Property Driven Development

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Abstract

Design process models are a central point of interest in engineering design research. Under this discussion, Characteristics-Properties Method/Property-Driven Development (CPM/PDD) has been a popular and widely applied theory for supporting the integration of product modelling and design process modelling. The theory has shown to be useful both in product development and production development. Yet, the theory has not been systematically used as part of continuous improvement of a manufacturing system. This study continues the development of the original theory and applies the theory to continuous improvement of product and production development. Information flow modelling method, that applies CPM/PDD elements, is used in four industrial case studies to coordinate development activity in integrated product and production development environment. As a result, the study proposes a conceptual model for coordinating Property-Driven Development. The theory aims to explain one possible and sustained means to coordinate continuous improvement in a manufacturing system.

Keywords: lean manufacturing; continuous improvement; information flow; integrated product and production development

1 Introduction

Characteristics-Properties Method/ Property-Driven Development -theory (CPM/PDD) has been actively applied and discussed in engineering design research (Gericke et al., 2020). Scientifically the theory has shown its usefulness in integrating many extant theories to one explanation model (Weber, 2014) and activated research on combining product modelling with design process modelling. On a practical level the CPM/PDD has been applied and further developed in mechanical engineering (Weber, 2005), software engineering (Conrad, Koehler, Wallach, & Luedeke, 2018), as well as in production engineering. However, the theory has not yet been applied systematically as part of continuous improvement of a manufacturing system.

The research objective is to propose a useful method to support lean manufacturing implementation in the area of high-variety, low-volume manufacturing (HVLV). HVLV manufacturers are characterized with longer customer order decoupling points, and represent engineering-to-order and manufacturing-to-order production strategies (Powell, Strandhagen, Tommelein, Ballard, & Rossi, 2014). In this context the ability to integrate product development and production development abilities is especially important.

2 Methodology

This study is a part of a larger research project. It follows the constructive research approach through which the concept of a novel, Information Flow Modelling method is developed. The study begins with a literature review of the three research domains of lean manufacturing, project management and engineering design. A synthesis of an initial version of the method was formulated based on the literature review. This is followed by empirical research in case studies, where case study research was applied in collecting and analysing the case study data. The research results provide a formalised version of the developed method and theoretical linkages to the research domains. The concept was tested in product development and production development projects in two simulated pilot case studies and seven industrial case studies in Finnish manufacturing companies.

Case Study Research is found suitable research method to systematically collect, analyze and describe empirical evidence of industrial projects (Yin, 2009). This paper covers four case studies of development projects done in HVLV manufacturing environment in Finland. The study uses rich set of empirical evidence from the cases consisting of direct observations, interviews, minutes, reports, publications, presentation materials and tangible deliverables of the case projects. In the case studies the Information Flow Modelling Method guides which CPM/PDD's elements to consider during development. It applies CPM/PDD elements as integral part of the approach as well as other typical continuous improvement elements. The IFMM follows three stages and eight steps (table 1).

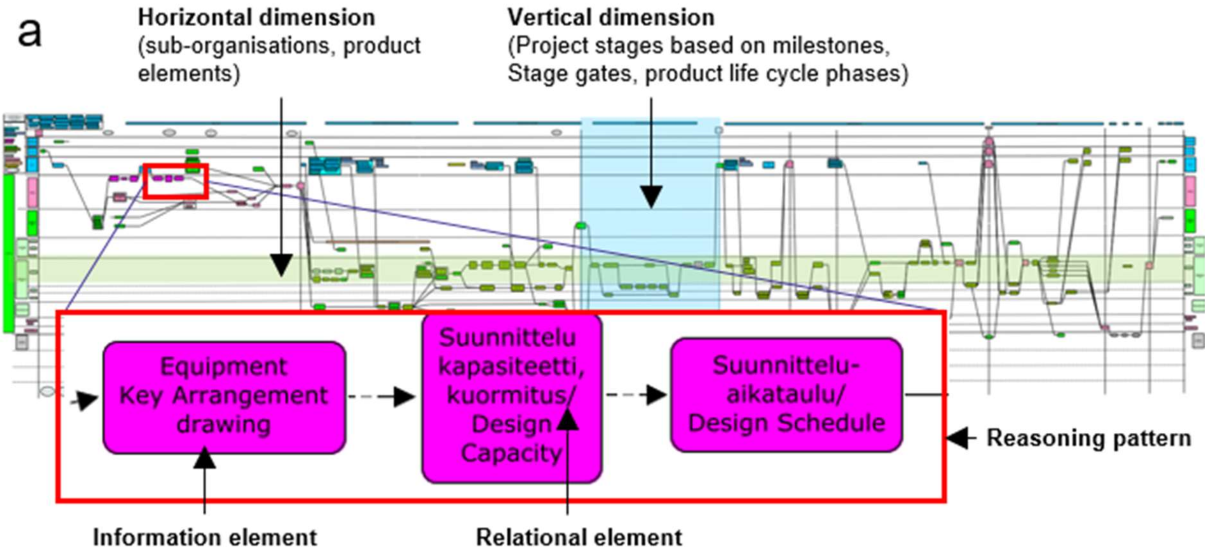
Table 1. Three stages of working method for CPM/PDD testing. The first stage is value structuring, the second flow structuring and the third transformation structuring.

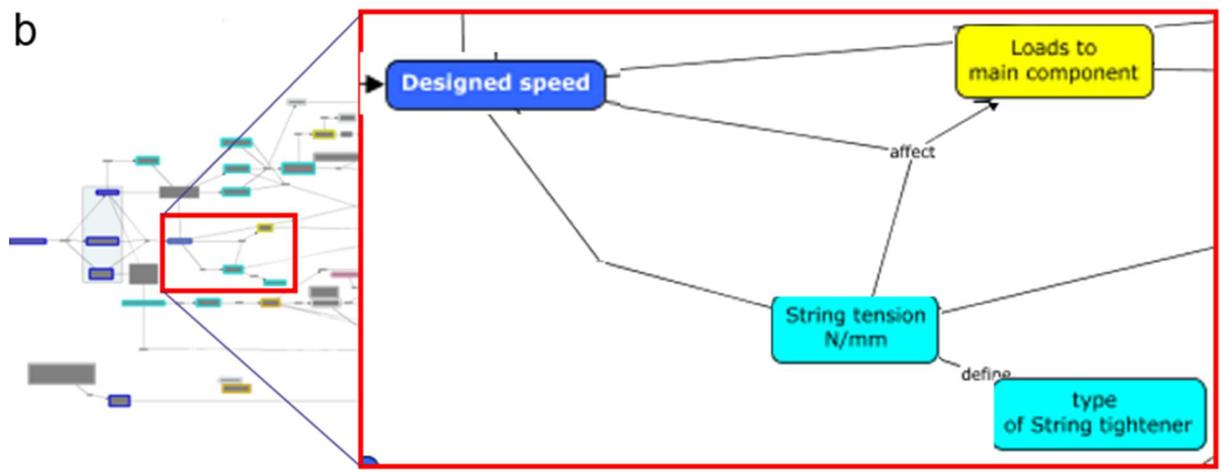
Value structuring	Flow structuring	Transformation structuring
1. Identifying current state: Value definition, Current state analysis	3. Identifying information elements: Identification of domains and information elements, Identification of attributes of information elements	6. Identifying development: Complementing information structuring, Formulation of solutions, Development project planning, Structured solution space
2. Setting goals: Defined and measurable goals, Future state analysis, Alignment of goals with current and future state analysis	4. Structuring information flow: Division logics of information elements, Organization of information elements with attributes	7. Continuous improvement: Development actions and decision making, Improvement navigation, Ownership and support for improvement system
	5. Connecting information elements: Dominant reasoning logics, Continuous information flow	8. Sustaining improvement system: Structuring improvement system, Improvement program management

In continuous improvement activity guided by the IFMM, first stage is to define value and goals for the development actions. In other words, the value system is structured to understand the current state of development, goals, and desires for future state. The second stage formalizes information flows of the development process based on practitioners' (product developers, production developers, managers) knowledge. Noticeable is that the steps in the second stage refer to formalization techniques, which may be used already during the first stage in identifying the current and future states of a manufacturing system. The third stage uses the formalizations of previous stages to guide and coordinate the actual transformations of the manufacturing system. The participation of all relevant project participants is critical in all stages.

In the core of the IFMM are the Information flow models and the modelling setting where the formalization of these models is enabled. An Information flow model consists of information elements, that are the lowest level of decomposed development activity addressing tangible and perceptual deliverables within continuous improvement. These information elements constitute of time-spatial captures of CPM/PDD elements along with other relevant variables such as work, material, control, or performance related information. Fig. 1 illustrates examples of formalized Information flow representing parts of a manufacturing system.

Fig. 1. (a) Product life cycle structuring of a delivery project; (b) Product life cycle structuring of a structuring of a design reasoning pattern of a component.





The method applies a dependency graph form of a multi-domain matrix to structure product, product life cycle (e.g., product development, production and delivery-projects), executable development process, value definitions and project coordination decisions. In align with a multi-domain matrix, the information flow models constitute of different structural domains that consider process related, organization related, and product architectural related aspects. A model captures dependencies between different domains and individual information elements or groups of information elements. A flow constitutes of sequences or patterns of information elements. The modelling setting follows a typical moderated workshop condition where a moderator builds the model in collaboration with the practitioners. In the case studies researchers worked as moderators. The setting applies different facilitation methods, relevant supportive materials such as technical drawings, process models, as well as direct observations of the manufacturing system. The modelling setting also follows specific design principles that steer reasoning towards Lean manufacturing philosophy.

3 Literature review

3.1 Research on CPM/PDD

The CPM/PDD -theory was introduced in the 1990's to model product and process based on product characteristics and properties. The theory integrates ideas from other commonly known theories in engineering design research, such as Axiomatic Design (Suh, 1998) and Function behaviour structure model (Gero & Mc Neill, 1998) and Product structuring (Andreasen, 2011). Characteristics-Properties Method is the product modelling side of the approach, whereas Property-Driven Development describes the development process. The core of the approach is the division of product into Characteristics (Cj) and Properties (Pj). Characteristics are the structure, shape, material consistency, dimensions etc., to which a designer or design team can have a direct influence or can determine on. Properties then again describe the product's behaviour, weight, safety, reliability, but also manufacturability, assemble ability, testability etc. The designer or design team cannot directly influence these. (Weber, 2005)

The strategy of Characteristics-Properties Method is to model characteristics and properties individually as well as interconnect them. The theory proposes two different relationship types between properties and characteristics, analysis (Rj) and synthesis (Rj-1). Property-Driven Development describes the product development process as a stepwise cycle with four typical steps of synthesis, analysis, individual evaluation and overall evaluation. Since its origination, CPM/PDD framework has been demonstrated to be useful in various applications. The framework has been examined especially from the views of design for X (DFX) (Greve, Fuchs, Hamraz, Windheim, & Krause, 2021), design knowledge (Duschek & Vielhaber, 2020) and lately in development of manufacturing systems.

The CPM/PDD framework can be viewed as a theory for DFX (Weber, 2014). Köhler uses the framework to support engineering change management (Köhler, Conrad, Wanke, & Weber, 2008). Kleeman demonstrates the CPM/PDD framework's usability in engineering design multi-optimisation challenge in automotive components (Kleemann, Fröhlich, Türck, & Vietor, 2017). Duschek uses an application of CPM/PDD to monitor different system properties of a product development project that aims to show the total degree of maturity in a more complex product development project (Duschek & Vielhaber, 2020). Similarly, CPM/PDD framework has contributed to research on design knowledge. Köhler (Köhler et al., 2008) find that the theory enables to structure design process knowledge, by reducing the process knowledge into relevant questions to be asked from CPM side of the framework. Conrad applies the framework in user centered design in software development and propose a design process that merges iterative process of user centered design with CPM/PDD steps (Conrad et al., 2018). Luedeke apply the framework in developing cyber-physical systems. The authors propose a methodology that consists of three stages of creative product development stage, agile product development stage and CPM/PDD development stage (Luedeke et al., 2018). Lately, the CPM/PDD theory has provided new means of optimization to manufacturing systems development. Already Deubel 2006 used the framework for requirement-driven planning of a manufacturing system (Deubel, Steinbach, & Weber, 2005). According to the authors transferring the CPM/PDD to model manufacturing systems is taking the external conditions of the original theory as a center point of examination. Halonen (Halonen, Lehtonen, & Juuti, 2014) apply CPM/PDD in developing delivery projects of an engineering-to-order manufacturer and consider product life cycle characteristics of external conditions to be decided in parallel with product chracteristics.

3.2 Continuous improvement

Continuous improvement (CI), equivalent to Japanese term Kaizen, can be seen as a bundle of routines which help an organisation to improve what it currently does (Bessant, Caffyn, & Gallagher, 2001). It is a form of dynamic capability, when it provides a comprehensive infrastructure to an organization to coordinate its resources towards to systematically improve and sustain the improvement (Glover, Farris, Van Aken, & Doolen, 2011). CI is often associated with Lean manufacturing, which is defined as "an integrated socio-technical system whose main objective is to eliminate waste by concurrently reducing or minimising supplier, customer and internal variability" (Shah & Ward, 2007).

CI and lean manufacturing although different, are strongly considered inseparable. For example Knol et al. have found that certain levels of CI routines are necessary in order to achieve more advanced levels of Lean manufacturing (Knol, Slomp, Schouteten, & Lauche, 2019). On the other hand, Netland (Netland, Powell, & Hines, 2020) promotes that achieving continuous improvement culture is the ultimate goal for implementing Lean manufacturing. Hines (Hines, Taylor, & Walsh, 2020) add to this that implementation of Lean manufacturing is a long term journey to develop a culture of improvement in a sociotechnical system, which should integrate strategy deployment, continuous improvement, leadership and systematic learning. It has been demonstrated that successful implementation start from implementing Lean practices, but later becomes more systematic and holistic program towards achieving CI culture (Hansen & Møller, 2016; Hines et al., 2020).

Successful implementation of Lean manufacturing requires systems-level development (Hines, Holwe, & Rich, 2004). It is well known that Lean manufacturing is more than just a set of practices (Shah & Ward, 2003) and should be deployed by the whole business (Womack & Jones, 1996). Already Fujimoto (Fujimoto, 2007) promote the Japanese view on production, equivalent to Toyota Production System, to view a manufacturing system across its individual organisations. The authors promote to examine a manufacturing system as a flow of design information where first the added value to the customer is met in design information during product development and later the design information is printed into physical media to become a final product (Takahiro Fujimoto, 2007). Dombrowski suggest to see Lean manufacturing as a framework that consists of practices, methods, principles and the development process (Dombrowski, Zahn, & Mielke, 2010). Lately project management has been increasingly combined with Lean manufacturing and continuous improvement. This is especially the case in

Lean manufacturing research related to high-variety, low-volume manufacturing, where project management routines are seen critical (Zennaro, Finco, Battini, & Persona, 2019).

Research on Lean manufacturing in HVLV draws on different means to address the project-based nature of the business and CI. For example Lean construction approach is proposed as a means to be used in Lean manufacturing in engineering-to-order firms (Powell et al., 2014). This approach is based on Transformation-Flow-Value -theory (TFV), which has been developed as an answer to weak theoretical foundations of conventional project management practices (Koskela, 2000). The transformation view links to a traditional view on seeing transformation as a black box through which inputs become outputs. The Flow view looks into production as a flow of operations focusing on total time and comprehensive process. This view relates to Lean manufacturing. The value view refers to defining value from the customer's perspective. This view is said to originate from the quality movement, which has introduced several different ways to describe customer requirement into manageable and measurable format (Koskela, Rooke, Bertelsen, & Henrich, 2007).

The view of project management in continuous improvement is largely on project portfolio and program management (Zennaro et al., 2019). Here, an interesting, yet emerging approach is lineage management, which has been identified to provide effective means to concurrent project learning as well as temporal cross-project learning (Midler, Maniak, & de Campigneulles, 2019). Lineage management is a special form of program management that originate from automotive industry. The lineage management focuses in enabling longitudinal knowledge accumulation across successive projects by coordinating knowledge building. (Maniak & Midler, 2014). This kind of view has generally been lacking in multiple-project management, which has primarily focused knowledge sharing between parallel projects.

In high-variety, low-volume manufacturing there is a lack of frameworks to support the implementation of lean manufacturing. The existing literature is limited to the shop floor and fails to link development activities to the firm's strategic goals. In addition, lean manufacturing does not sufficiently consider product development in this context. Project management seems to offer partial solutions in linking improvement projects to strategic levels of manufacturing but requires long-term systematic efforts and knowledge accumulation across individual projects.

4 Empirical research

This section presents the four industrial case studies. Each case study description presents the driving problem for the development project and then points out the different actions and elements related to applying CPM/PDD.

4.1 Case 1

The first case study is a production development project executed in an automotive firm. The firm was building entirely new production line. The production development was done on engineering-to-order basis. The case project was a sub-project within the overall project to find means to make the project coordination more efficient. The development started by back casting the development process of the entire production development project in order to improve the understanding of the current state. This was done by formalizing the process in collaboration with practitioners. Here characteristics were related to different decisions in the production project such as layout decisions in the factory floor and specifications for certain production machinery. Desired properties were summarized as an ability to produce the specified automotive products with an expected quality level. Soon, it was discovered that this orientation was too time consuming given the tight schedule of the project.

The second orientation was decided to focus on describing relationships on the active project plan by building relationships based on researcher's know how on similar projects to capture the critical path. The original plan did not consist of relationships between tasks. This approach was soon also found impossible under the project conditions due to the project plan's inaccuracies. At this point, the maturity level of the project management routines within the firm was identified. The orientation was aligned to provide more basic project management support for the overall project. This was done by piloting project planning and monitoring routines in a sub-project. As a result, this improved the efficiency of the sub-project management and decreased the work for monitoring the progress of the sub-project.

4.2 Case 2

The second case study is a product development project executed in an engineering-to-order heavy machinery manufacturer. Company wanted its products to become more configurable and decrease costs. The case project covered a sub-project where a principal solution for a component in the overall product was developed. The project coordination was already decided prior to development. The sub-project was one of the first projects to initiate the broader development program. The development started from value structuring, where primary expectations and limitations were defined for the development actions. This was followed by product structuring, where the developed component was divided into generic architectural elements. After this, a design process was described. Here, characteristics represented architectural decisions, mechanical specifications, material decisions, production techniques while primary desired properties were decreased costs in balance with new market needs. Actual properties were simulated using a total cost of ownership analysis method that described the design, production, material and control costs related to the component. The chosen orientational conditions focused in finding an acceptable solution principle in close collaboration with practitioners.

During the value structuring, over quality was found on systems level in the existing products. This was needed to be addressed in the development actions by intervening practitioners, because the practitioners themselves did not identify problems. The researchers decided to provide development orientation where longitudinal reasoning relationships of the decided product characteristics and their effects on product properties are visualised together with the practitioners in order to facilitate the intervention. As a result, the practitioners identified the problem, the historical design margins were questioned and the project was able to come up with solution principles that significantly reduced the production and material costs of the component.

4.3 Case 3

The third case study was a product development project executed in an engineering-to-order heavy machinery manufacturer. The company needed to improve its prototype testing and documentation routines in an active project. Prior to the project the value was structured in the form of goals for an improved situation. The development project aimed to provide more standard documentation routines and support for the complex technical problem solving in the active product development project (desired properties). Product development had faced time pressure and and come across critical challenges in finding sufficient solution for a technical problem. The development was started from studying and experimenting on the prototype.

Concurrently with the first step, a working testing- and documentation protocol was created. After this orientation was put into structuring the testing conditions including the prototype construction, process parameters, input and output variables of the testing. This aimed to formalize an understanding of the feasible solutions space for the developed prototype. This meant that instead of formalizing a systems model of protype behaviors, the target was to use the model to narrow down the possible solutions based on valid information from the test results. By applying of formalized testing conditions to navigate the testing steps the developers were able to identify that the desired properties were not able to be found within the current solution space with given solution patterns.

The formalizing of testing conditions as an orientational variable provided critical means to systematically proceed and accumulate knowledge during the overall product development project. As a result the practitioners were able to find a satisfying solution within the given time limits.

4.4 Case 4

The fourth case study was an integrated product development and production development project. Here two projects were executed in parallel, a product development project creating a new product generation and production development project to renew the existing factory. The case project concerned the project planning and coordination of the initial steps of the development projects. The development was started from value structuring. This aimed to create better shared understanding of the baseline of the production and product development.

Product structuring and production structuring was used to define limitations and expectations for desired properties as well as solution space limitations for product and production characteristics. Value structuring made also clear the difference of what were the target properties that are expected and measurable from the actual development projects and what are more long-term desired properties. After this development process was structured. A formalized information flow covered a long-term view to development process providing insights into in which order characteristics should be developed and properties should be realized both in product development and production. The information flow was formulated into a project plan that provided sequence, resources, and practices to be used as orientational variables in different points of the development projects. The developments in both projects were coordinated with the help of the project plan.

The formalized development process offered orientational variables that were aligned accurately with the current states of development including the development culture. The first coordination steps were therefore able to provide state-of-the-art product development approaches, DFX approaches as well as efficient collaboration routines to enable more systematic progress in the actual development.

5 Results

The empirical results demonstrate that the coordination of development steps benefited from applying CPM/PDD in all the development projects. Based on the empirical insights a concept for a theoretical framework of Coordinated CPM/PDD was formulated (fig 2). The original CPM/PDD theory description was extended to better align with the systems level development of continuous improvement activities found in the case studies. The original elements of CPM/PDD are situated as part of formalized development process knowledge within the captured information elements along with the orientational variables that are also teleologically controlled in coordination routines. The Value drivers are situated below analysis and synthesis, having guidance from Coordinative Information Flow, which also guides the intended artefact characteristics. In the framework, characteristics address all the elements that can be influenced by the practitioners or managers of the manufacturing system. The deviations between actual and desired properties are translated to a pulling effect for coordination and actual development steps on multiple project level. On single project level the deviations are allocated into target properties that contribute to the lineage of more long-term development. Within different stages and sub-deliverables of the projects the target properties are further decomposed into target maturity levels.

In the original theory the synthesis and analysis are done on product development level. In this situation product structuring may be feasible. However, in the development of a sociotechnical manufacturing system, the structuring must be able to address the systems level phenomena. Therefore, the new framework promotes structuring to be done on five levels. First level is value structuring that constructs descriptions that support defining current state and measurable goals for development aligned with company strategy, market, and network. Second level is multiple-project structuring. This level describes and allocates development actions into coordinative and executable form. The third level is development process structuring. This level formalizes information flow of the sub-deliverables needed in a logical sequence to enable target properties/deviations in the end of planned project. The fourth level is product structuring that constructs different views to the developed or produced product to support design or other functions. The fifth level is process structuring that describes different views to a manufacturing system combining perspectives of external conditions (such as standard routines and use environment).

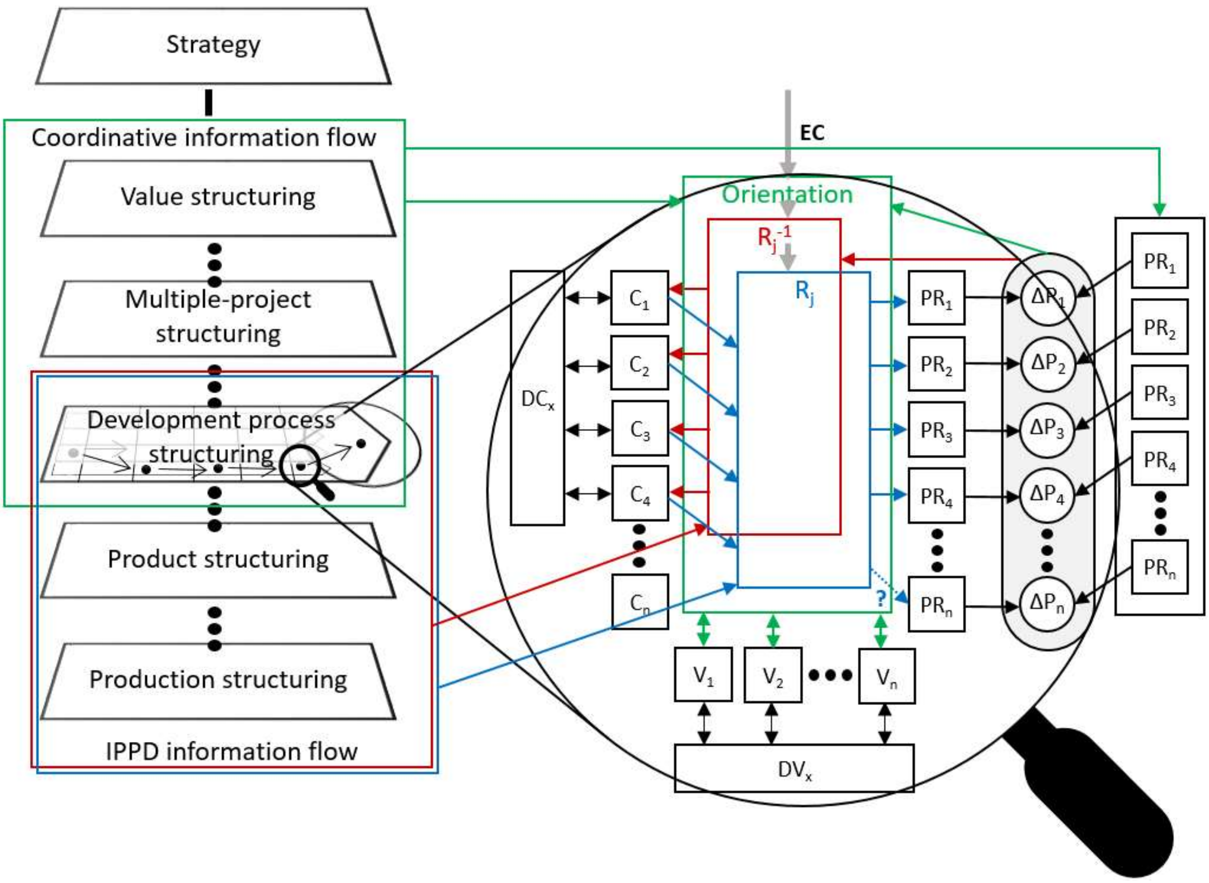


Fig. 2. Coordinated Property-Driven Development

However, the ability to formalize and coordinate systems level development activity is enabled only by linking the different levels of structuring and focusing in limiting the constructions into views that are useful for the development. In the Coordinated CPM/PDD framework, the information flow that is useful for the coordination purpose of the development focuses on the perspectives of value (aligned with strategy), multiple-project and development flow. The information flow that is useful for the actual synthesis and analysis within development actions focus on product, process, and development flow.

6 Conclusions and discussion

The study shows that CPM/PDD can be successfully used in continuous improvement of product development and production. The empirical evidence indicate that the framework is useful in enabling the formalization of customer value into tangible and executable steps. Together with formalizing information flows of a manufacturing system, CPM/PDD elements provide orientational support for actual development steps.

The novelty of the proposed concept of Coordinated CPM/PDD is that it is the first time the original theory has been demonstrated to be useful in continuous improvement context. In addition, the coordination view is new. The study demonstrates one possible means to use CPM/PDD information to support the coordination of development actions not just on single development project level but on multiple-project level.

The study does not come without limitations. Firstly, the proposed extension for the CPM/PDD is a concept based on explorative research. Future research should be able to build on the identified theoretical description and define the newly introduced elements more accurately. Secondly, this study presents systems level development, meaning developing the development. This is the main reason why this study does not cover a closed multi-optimization setting as have been demonstrated in the previous applications of CPM/PDD. Thirdly, the study was organized within HVLV manufacturing, which must be considered in examining the generalizability of the results. However, in the case studies the evidenced sociotechnical problems are something that are universal across manufacturing sectors. Thus, it is highly anticipated that the results can be generalized also to more repetitive manufacturing.

One interesting direction for future research is looking into the similarities of Coordinated CPM/PDD in relation to lineage management. Based on the findings the original CPM/PDD theory provides promising applications that can be used similarly to coordinate knowledge across development projects.

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