Strategies for Integrating Preparation and Realisation – The Case of Product Models[1]

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Abstract

The purpose of this paper is to discuss the integration of the Product Model (PM) and the Product State Model (PSM). Focus is on information exchange from the PSM to the PM within the manufacturing of a single ship. The paper distinguishes between information and knowledge integration. The paper provides some overall strategies for integrating PM and PSM. The context of this discussion is a development project at Odense Steel Shipyard (OSS).

Keywords: Manufacturing, Preparation, Realisation, Product Model, Product State Model, Integration Strategies, Conditioning.

1. Introduction

IT-support of the manufacturing processes have been practised for several years, e.g. computer aided design (CAD), computer aided manufacturing (CAM), computer aided engineering (CAE), and computer integrated manufacturing (CIM). However, in relation to information exchange and functional alignment through the lifecycle stages of the product (from cradle to grave), this development has often resulted in isolated solutions of IT-support, although integration initiatives have been established.

The fundamental idea of the global initiative named Continuous Acquisition and Lifecycle Support (CALS) is to achieve an effective exchange of information throughout the stages of the

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product lifecycle. CALS has been applied in a military context for more than 10 years. However, in relation to commercial industries this is still an immature research area.

Product related information is based on models, which describe the product with respect to its structure, applied methods and eventually facilities for production of the product.

The focus of this paper is primarily the integration between two specific types of models, i.e. the Product Model (PM) and the Product State Model (PSM). The PM contains information generated during design, methods engineering and production planning, whereas the PSM contains data with regard to the outcome and results of the production process and the corresponding real life state of the product and/or its subparts during production.

The objective of the article is to investigate specific aspects and possible potentials regarding the application of PM and PSM in order to describe the integration between the PM and the PSM. For example as feedback, e.g. evaluation of the adequacy and producability of a design; and feed forward, e.g. redesign of subparts to fit already produced items or for re-scheduling of production, based on information on the realised state of subparts. Integration can be considered with respect to information and knowledge between tasks/functions in the overall manufacturing system - not least quality assurance during production and maintenance & support in the operation phase of the lifecycle.

As the PSM in our opinion is not yet a recognised topic in the research community, it is relevant to introduce a discussion of the Product State Models interfaces with Product Models. By introducing the PSM, product modelling is extended from the previous application areas of design and product preparation to the production. The concept of PSM is also applicable further on in the product lifecycle, however, at aim in this paper is to consider the design-production relations, focusing on the information collected at the shop floor and send to the design/specification product model.

2. Problem Identification

Manufacturing of today has developed excellent skills in producing in accordance to design specification. Nevertheless, process deviations, accumulated tolerance errors, changes in customer demands, and humans errors might cause product parts, which do not completely fulfil the specifications. In some situations these products can not be scrapped due to a high cost binding in the product. Hence, the divergences have to be evaluated and proper compensation/rework must be undertaken. One of the purposes of introducing a Product State Model, originally suggested by Lynggard (1996), is to be able to change the specification/design model during production in order better to fit the product parts to be produced to the already produced parts. This situation is called feedback[i] of information.

By producing the product part on the basis of information on the already produced part, and not on the basis of what was originally planned, which is the traditional manufacturing practice, it is intended to reduce the deviations from design specifications accumulated through the production. Hence, a better quality, shorter lead-time, and reduced costs can be obtained. Changing the design model during production requires effective feed forward of information. This requires monitoring of state changes (planned compared with realised states) and the initiation of corrective actions to compensate for the changes. The research question is how a PM and a PSM can be integrated? This question will be regarded from a theoretical as well as an empirical point of view. The theoretical aspect concerns the prerequisites for the conceptual and functional integration of the two models, whereas the empirical aspect concerns some of the elements, which have to be taken into account in an empirical setting.

3. Research Methodology

This section provides the scope of the article, presents the research question and hypotheses, delimits the research question, and describes the approach for development and test of the hypotheses.

3.1 Scope of the Article

Information exchange can be regarded from several viewpoints, cf. Figure 1. Firstly, within the lifecycle of an individual product. Here, information can be sent forward to support later activities or feed backward to earlier lifecycle stages, e.g. product state is used by design, specification and planning for adjusting the product model. The second viewpoint is information exchange between different lifecycles, e.g. collection of data from one lifecycle can be used to improve future products. This is current practice in the classification of ships (e.g. DNV and Lloyds), where the classification societies collect historical data about the ships including failures, and uses this information to improve guidelines for shipbuilding. However, information exchange is only to a limited degree supported by information technology.

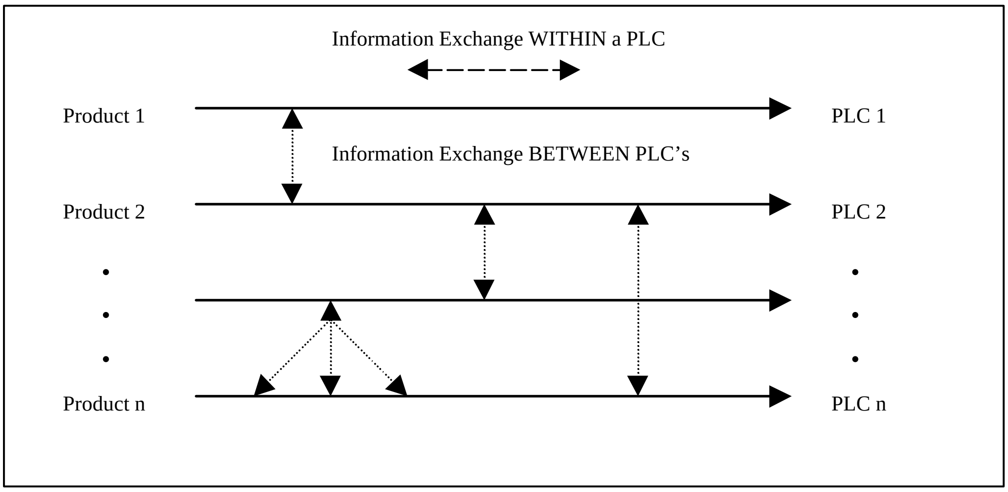

Figure 1: Information Exchange within and between Product Lifecycle's.

The focus of this article is information exchange within a product lifecycle. Information exchange in a lifecycle perspective is the primary concern of the Continuous Acquisition and Lifecycle Support (CALS) initiative, cf. Miller et al. (1994), Magnusson & Holm (1996), Mase (1996), and Larsen et al. (1997, 1999).

The empirical domain of the article is the ship building industry. This industry is characterised by low product volumes, long throughput times, high prised products with long lifecycles. Primarily, the characteristics of high prised products and long life are important factors when considering the cost-benefit of developing a product state model. In particular, Odense Steel Shipyard is in focus due to the fact that the author in co-operation with the shipyard are involved in two development projects, i.e. CALS Center Denmark and the BRITE-EURAM project QualiGlobe. The projects deal with different information exchange issues with regard to product state.

3.2 The Research Design

The approach adapted in this article derives from Jørgensen (1992). On the basis of the problem base, an analysis of the needs of Odense Steel Shipyard to develop a Product State Model and integrating it with the Product Model is carried out. A diagnosis, concluding the analysis, is the basis for the development of solutions.

The empirical problem base is intended to motivate to synthesis. Lack of an existing theory describing the integration of a Product Model with a Product State Model, leads to the development of some integration strategies, which are considered as the foundation for future research. As sufficient theory does not exist and as the Product State Model is not yet implemented at the shipyard, the paper terminates at the synthesis of theoretical work.

4. The Empirical Foundation

4.1 General Challenges at Odense Steel Shipyard

Odense Steel Shipyard (OSS) is among others producing the world largest container ships. The company is one of the few Scandinavian shipyards, which have survived and prospered in the strong competition of the last decade. Hence, OSS has been able to deliver their products timely and in a high quality. As competition is becoming even harder, OSS continuously thrives to improve the efficiency of their processes. When trying the enhance the efficiency several quality, resource and time related problems resulting in inconsistent geometry, accumulated tolerance errors, long through put time, unnecessary use of resources etc. are encountered. These effects are caused by a variety of problems related to e.g. lack of information acquisition and integration, production procedures, systems, and people, cf. Larsen & Bilberg (1998). The purpose of introducing the Product State Model at OSS is primarily to improve the production process by reducing the effects of inconsistent geometries and preventing accumulated tolerance errors.

4.2 The Product Modelling and Planning at Odense Steel Shipyard

The PROduct Model of Odense Shipyard (PROMOS) integrates the diverse CAD systems applied at the shipyard. The repository of the PROMOS system is a distributed object oriented database, Basu & Mikkelsen (1997). CAD systems are used to create the geometries presented as three-dimensional models by PROMOS. Production planning such as defining building sequence and weld patterns is carried out in PROMOS. Scheduling is not included in PROMOS, but defined in a separate production management system.

4.3 The Case of Panel Assembly and 2D Measures at OSS

This case, which is highly influenced by QualiGlobe Working Group at OSS, has focus on state changes in two dimensions. It shows the conceptual idea of collecting data from the shop floor of the production and feeding the relevant product state information changes forward to the product model.

The objective is to produce panels without margin, e.g. over-length, as of today but with a tolerance of +/- 2 mm., for panels up to 32 x 20 meters in size with varying thickness (10 to 25 mm).

The case provides an analysis of the current situation at hand. Successively, a potential gain by introducing a PSM is proposed. Finally, the results obtained are generalised.

4.3.1 Process Description

The scope of the case is the sub-assembly and assembly of deck, tank top and bulkhead panels. The activities of the case are illustrated and described below:

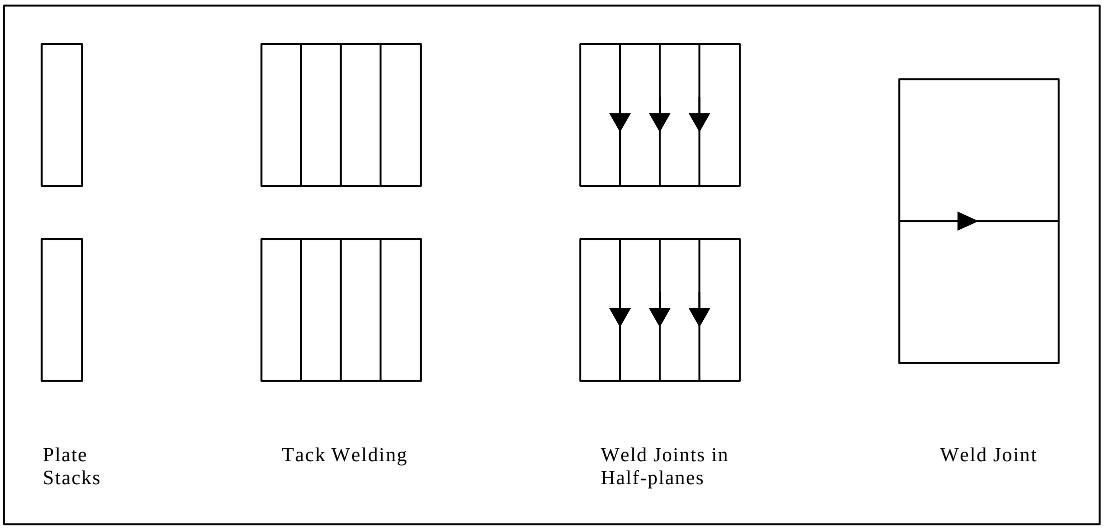

Figure 2: Assembly of a full panel.

The flow within the scope of the sub-assembly is going through the following stages:

- *The Plate Stacks.* The plates are brought in from the ship building area by conveyor, where they have been measured. Then the plates are sorted in stacks in accordance to the assembly. The plates may be marked with assembly lines.
- *Tack Welding.* The plates are transported from a plate stack by crane and placed on the working space. The plates are then lined up[ii], and tack-welded to form a half-panel (16 x 20 meters).
- *Weld Joints in Half-panels.* The half-panel is then rolled forward to the welding station. The welding parameters are determined, and the half-panels are welded. The weld is then inspected, and in case of errors, reparation takes place in a ditch.
- *Weld Joint in full-panel.* The two half-panels are then rolled forward to be prepared for welding. The half-panels are tack welded and form now the full panel (32 x 20 meters). Gabs in contact points are measured and registered. Weights are placed on the panel to align the half-panels. Welding parameters are determined and the half-panels are welded. The welding is visually inspected. The panel is manually marked if the plates are not marked in the cutting process. Otherwise, the marking is inspected.

4.3.2 Process Analysis

During the above mentioned process the product changes its state. The assembly of plates and half-panels is intended, but the processes applied imply 2-dimensional variation in the output due to effects of inaccurate lining (misalignment) and shrinkage, due to heat input. Further more, other state changes occur. E.g. out of the plane deformations (change in the 3rd dimension), thermal properties of the material in the heat affected zone, and metallurgical properties of the material in the heat affected zone. These variations are however only considered to a limited extent or not at all in this case. The state changes are:

In order to reduce or eliminate undesirable deviations from design specification, compensation is done by the use of weights to control out of the plane deformations and by reparation of welding errors. Otherwise, the panels proceed to the next production step without any further correction or preventive information provided. In extreme cases, the outer dimensions of the panels have to be rectified by grinding or cutting of the extra lengths.

As of today, inspection is carried out in order to collect quality information, by ultrasound inspection of all outruns (i.e. approximately the last 30 cm of a welded join), and visual inspection at all welds.

The human factor also plays an important role in the quality of the assemblies. Though the production process can not successfully be completed without the involvement from people, it is also affected by human errors, during manual marking of panels, positioning of the plates and half planes, positioning of weights on panels (causing stresses in the panels), visual inspection, and measuring procedures.

4.3.3 Proposed Process Improvements

The process could benefit from the introduction of a 3-dimensional measuring system (MONMOS[iii]) at the following stages in the process as continuous measurements and adjustments might reduce the accumulated deviations.

- *Tack Welding.* After the tack welding the half-panel should be measured by the MONMOS system to check the result to the welding.
- *Weld Joints in Half-panels.* After the half-panels are welded, measuring with the MONMOS system should be done to inspect the panel and determine shrinkage.
- *Weld Joint in full-panel.* When the two half-panels are then rolled forward, the half-panels should be adjusted in accordance to MONMOS measurements. Also after the half-panels are welded, measuring with the MONMOS system could be done to inspect the panel and determine the shrinkage.

The table below illustrate the potentials of the process improvements, the likely benefits, those who will benefit from this, and finally the success criteria of the improvement.

Potential Improvements	Benefits	Beneficiaries	Success Criteria
Overall weld quality	Higher strength, quality, profit, efficiency	All involved	Control heat input
Continuous inspection	Quality improvement and overview	All involved	Useably data in PSM
Documentation of Dimensions PSM storage	Improvement of availability of measured dimensions for post users	Foremen, operators and receivers of the product	Easy use and storage
Shrinkage measurements	Better estimation of shrinkage	Shrinkage manager, Designers	Obtain useably shrinkage factors, and develop a shrinkage database
Weld Data storage	Inspection and monitoring of weldings	Shrinkage manager, Designer	Transfer of PSM data to the shrinkage estimation program
Inspection of welding quality “scatter parameter” window	Quick and traceable weld inspection	Operator, classification society	An operational system
Reduce accumulated errors	Improves production efficiency	Downstream activities	Being able to measure errors

Table 1: Potential Improvements, Benefits, Beneficiaries and Success Criteria.

In this case, the beneficiaries of the product state information and state corrections are the successive production steps. These benefits are expected to reduce the potential accumulated errors when dimensions are continuously controlled.

4.4 Synthesis of the Empirical Study

The underlying assumption of manufacturing practice of producing exactly to specification is taken up to reconsideration by introducing the concept of a Product State Model. A zero-defect/error focus is not compatible to the existing technology and production procedures of today's ship building industry. Nevertheless, this should not indicate, that the ongoing research for reducing errors should not still be pursued.

The problem of obtaining sufficient quality still remains. Process deviations can be reduced but not eliminated. Deviations are unavoidable during manufacturing, and often they will affect later production stages or other parts of the organisation. Hence, action must be taken in order to compensate for the occurred deviations. Hence, product state information has to be provided to later production stages or other parts of the organisation in order for them to be able to perform corrective actions.

The observed deviations in the production are seldom the root causes of the errors. Often, only the accumulated results of deviations are observed. The causes of the accumulated deviations can be assigned to the frequency and magnitude of the individual occurrences. The frequency is rather difficult to reduce, e.g. as each machine operates with a certain uncertainty. However, with respect to the magnitude of the accumulated deviations, it is the intention that these can be reduced significant. This can be achieved by monitoring every stage in the production process, determining the state of the product parts, and finally informing later stage about the state deviations from the planned specification, in order to take preventive or corrective action at these later stages. When the deviations are related to characteristics in the design, specification, and planning, then corrective actions demand changes of the related models. Hence, the product models for design, specification, and planning have to be integrated to the Product State Model.

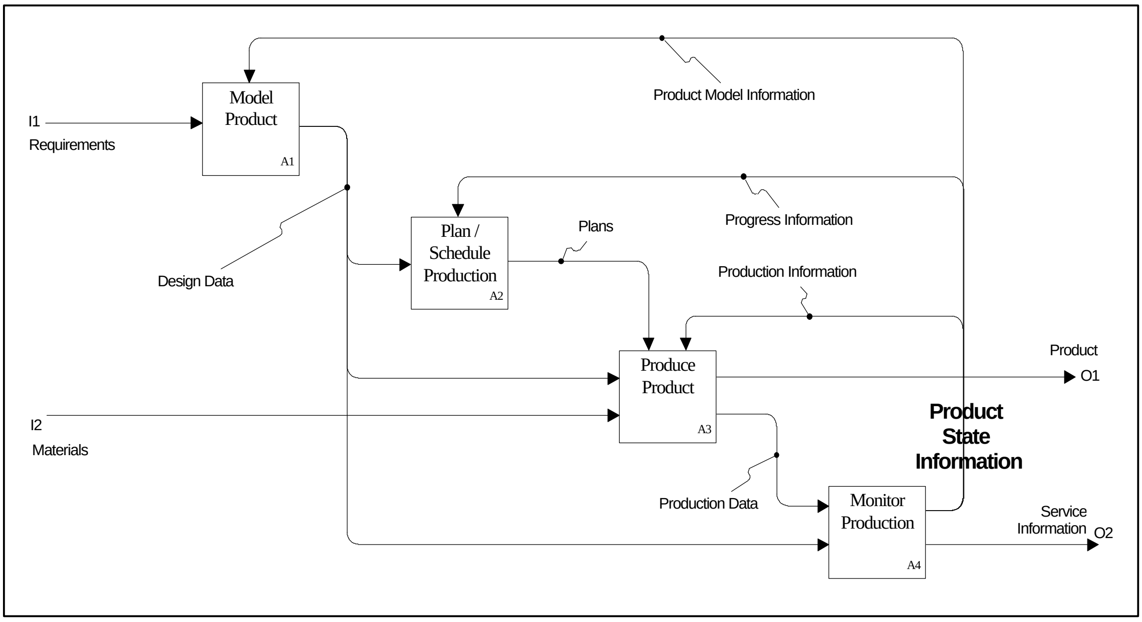

Figure 3: Exchange of product state information.
Source: Origin by Odense Steel Shipyard, and modified by the authors.
Remark: Note that the context of the IDEF0 is the manufacturing of Ships.

Changes in manufacturing procedures are then going from “model-plan-execute-monitor” and “replan-reexecute-remonitor” procedures to “model-plan-execute-monitor” and “remodel-replan-reexecute-remonitor” procedures, cf. Figure 3. In other words, the product is remodelled.

Figure 3 illustrates the principles of the Product State Model, where product state information is fed from Monitor to Execute, Plan and Model, respectively.

Today, manufacturing companies have the capability to feeding product state information fed forward (in time) to “Execute” and “Plan”, however, feeding product state information forward to “Model” is new.

These considerations raise the question of how to integrate the model of design/plan/schedule with the model of the realisation, i.e. the product state model. The essence of Figure 3, i.e. integrating the design/plan/schedule model with the realisation model, is illustrated in Figure 4.

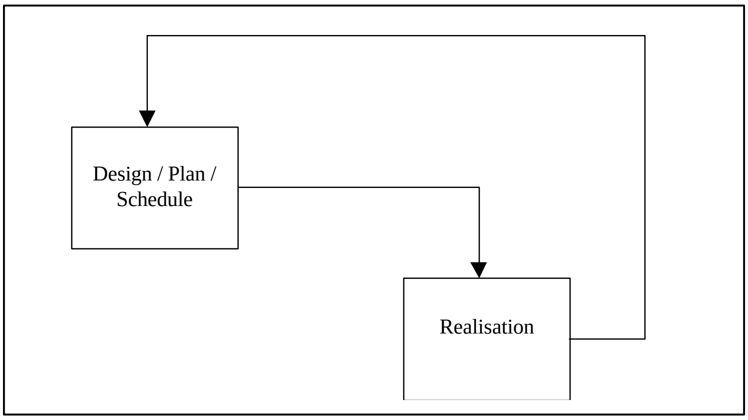

Figure 4: Integrating Design/Plan/Schedule with Realisation.

When integrating the two phases the implications of changing information in the design/plan/schedule model has to be considered. I.e. what are the implications? This will be elaborated in the following.

5. The Theoretical Foundation

The theoretical foundation supporting the principle idea of integration the realisation with design/plan/scheduling, cf. Figure 4, is to distinguish between knowledge and information integration. This leads to an investigation and consideration of current literature on the relation of Design and Manufacturing.

5.1 Product Modelling and Exchange of Product Related Information

The representation of product related information at all relevant manufacturing stages is based on the model, which describes the product and the management and distribution of this information. A Product Model (PM) and product modelling are defined by numerous contributors, e.g. Mäntylä (1989), Kimura (1989), Shaw (1989), Young (1992), Krause et al. (1993), and Andreasen (1992). Young (1992) defines product modelling as "… the mechanism by which a central source of product data can be captured to provide an integrated mechanism between a range of design and manufacturing functions". However various different views on product models exist. A common perception is that the product model, in order to form a complete specification for the product, should be interrelated to other types of models. Krause (1989) identifies four such models: 1) The product model, which contains geometric description, structure description, and process description. 2) The factory model, entailing an equipment model, capacity and scheduling model, and a plant layout model. 3) The process model, which contain an operation model and a tool path model. 4) The application model, containing application knowledge derived from service and maintenance. The process model regards the planned operations in the production domain, whereas the application model contains experiences from the domain of operation.

In addition, Krause et al. (1993) relates product models to different views on the product. Information can be related to specific lifecycle stages such as design, production and dismantling, i.e. the implications of decisions to the future of the lifecycle. Different views also include stages of concretisation of the product such as required, proposed and realised. Traditionally, the focus in product modelling has been placed on the definition of the product as an output of design/specification/plan process, while the realised product has not received similar attention. Krause et al. (1993) include both aspects in product modelling, but this article refers to product model as the result of the design/specification/planning synthesis proposing how the product should be, where as PSM is related to the characteristics of the realised product.

Product models can serve different purposes. Christensen (1996:54) concludes on his review of product models for ships: "… the Europeans and Americans focus on efficient exchange of product data whereas the Japanese and the Koreans focus on efficient generation of information". Krause (1989) and Krause et al. (1993) suggest four types of product models: 1) A structure oriented PM describing the breakdown of the product e.g. bill of material and classification structures. 2) A geometry oriented PM defined as "computer internal models with the primary purpose of representing the shape of one specific product" (Kimura, 1990). This kind of PM include wire frames, surface models and solid models. 3) A feature oriented PM is an extension of the geometry oriented PM as features represent shape patterns with a specific semantic meaning with respect to the design or manufacturing process. Allada & Anand (1995) provide an overview of feature-based modelling. 4) A knowledge based PM which use artificial intelligence techniques e.g. rule based reasoning, constraint modelling and truth maintenance systems, cf. Lu (1990).

Krause et al. (1993:700-701) argue that a product model has to be closely related to process chains - also are referred to as product development workflows or product modelling processes. Process chains can be with, without, or with integrated PM's. In order to achieve full benefits of the feedback process of cf. Figure 4, faster and more automated recycling of the design/specification/ planning should require adequate support by the PM. Hence, the product model would integrate a feature oriented product models with a knowledge based product model, because interrelations of the structured data and its functional properties.

5.2 Specifying Products - Domain Theory

The Theory of Domains (Andreasen, 1980) explains product development as a synthesis of four different views on the product (domains):

- *Process.* The process domain describes the interaction between the product, the operator and the surroundings.
- *Function.* The function domain describes intended functionality in the product.
- *Organ.* The organ domain describes materialised design solutions, which provide the product's intended functionality.
- *Part.* The part domain contains a description of the physical components and assembly structures.

Within each domain, the product can be specified from abstract level to concrete as well as from simple description to a highly detailed. The final specification of the product would have to be detailed and concrete as needed in order to produce the product. Hence, the designer moves from simple abstract representations of the product towards a detailed and concrete specification. This process is known as the horizontal synthesis, cf. Figure 5. In addition, causal relationships of the product must be identified and mapped within and between each domain through vertical synthesis. E.g. domains are linked together a process may determine a specific functionality, which is realised by a certain organ, which consist of a set of parts.

In practice, the four domains are not determined in a fixed order, cf. Andreasen (1980), but depend on the experience of the individual designer, his/her working methods, and patterns of thought and ability to abstract. Buur (1990) argues that “The process of machine synthesis cannot be described in a simple sequence of activities belonging to each domain. The designer is likely to jump back and forth between the four perceptions of the machine”.

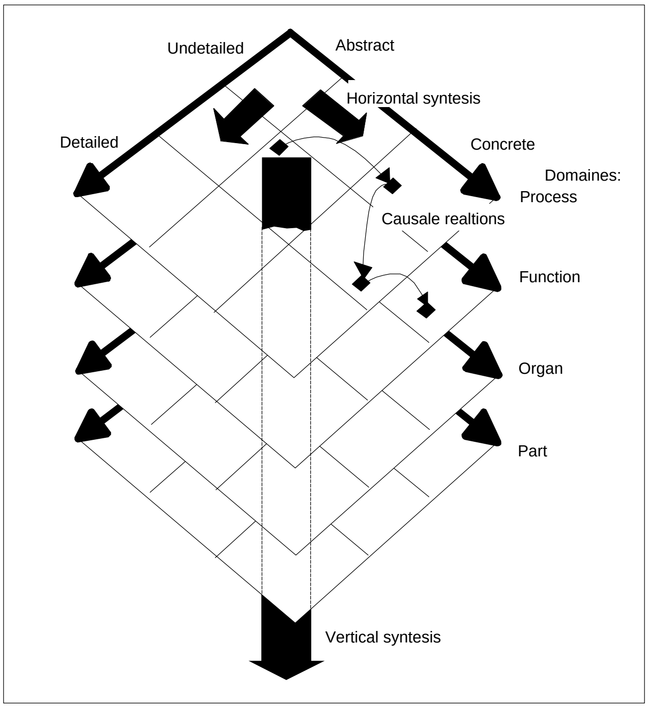

Figure 5: Synthesis with the domains of Domain Theory.
Source of figure: Grothe-Møller (1998).

Products are assigned to two types of product attributes, i.e. characteristics and properties. Characteristics define the product by the four domains. Properties are defined as the derived attributes, which can be determined after the characteristics are set. Depending on context, cause-effects between and within domains can be implications or bi-implications, i.e. the implications can be drawn in both directions. Cause-effects are difficult to determine and may be indirectly assumed through the process of synthesis. Consecutively, it is difficult to develop knowledge based systems based on rules, which are required when changes in a product model has to be considered in relation to its cause-effects.

5.3 Synthesis of theoretical work

The conclusions of the theory investigation suggest that the existing body of theory only provide a limited insight in how to handle product deviations in relation to product models. Hence, a search for strategies or classification schemes is of relevance.

An integration of PM and PSM must consider the level of integration; either an informational or knowledge based level. Vesterager et al. (1994) distinguishes between knowledge integration and information integration. Information integration exists if different functions exchange information based on the same semantics. Information exchange is a prerequisite for knowledge integration. Further more, knowledge integration requires co-ordination of the ways, in which the functions can be conducted. The information exchange co-ordination between functions is considered as a viable analogy to information exchange and co-ordination between product models. Hence, it is a useful concept in considering the integration between the Product State Model and the Product Model.

The current literature on the relation of Design and Manufacturing is primarily focused on Design for Manufacturing (DfM), e.g. Fabricius (1994). Focus is on feature extraction, i.e. a hierarchical decomposition of the functional properties of a certain product leading to a certain number of representative structured data through causal relations. In short: F → S, cf. the down stream of Figure 6.

The problem at hand is however of the opposite nature (Manufacturing for Design). This problem is about continuous re-evaluation and updates to the product model based on the realised product state. A deviation in the specified parameter (ΔS) is related to the planed value of the parameter (S) and the functional properties (F) causing S. In short: ΔS → S → F. Figure 6 illustrates the change in structured data. For example, the structured data with value S1 deviates from specification. Hence, appropriate action must be taken to evaluate the significance and implications of the deviation, cf. section 5.4. The corresponding value, S1‘, is identified and it is examined whether changes in S1’ to S1 has implications on the functional causal functional properties (F1’) of S1’.

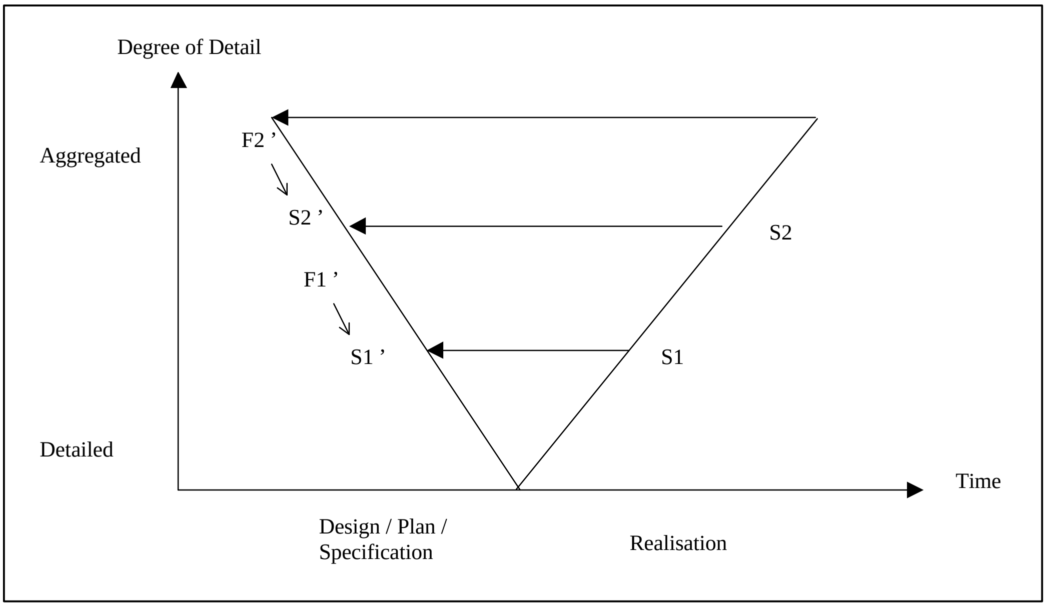

Figure 6: Evaluation of structural data and its functional properties.

The implications of changing a certain structured data in a product model have multiple facets. For example, what are the implications of a joint of two steel plates when it is moved a bit to one side? Would the contact points of this section fit with the next section and can the structure maintain it’s strength and stability?

Summing up the theoretical considerations and synthesis, integration with the product model has to be on a knowledge level in order to incorporate the functional properties of the parameters in the PM, and not solely on an informational/semantic level.

6. Strategies for the Integration of PSM and PM

A product as complex as a ship, can be considered as a system. A system is characterised by it components and their interrelations, e.g. the F → S relations above. The causal relation effects of product state deviations can have different consequences on the overall system. This effect is defined as the system dependence. E.g. the effects of a product state deviation could affect the global system (the entire ship performance), be limited to local consequences or have no consequence at all. System dependence, cf. Churchman (1979), requires a multiple view perspective in order to determine all possible causal relations. E.g. the causal relations does not only include geometrical aspects of the product but also considerations with regard to the lifecycle of the product, i.e. dispositional mechanisms cf. Olesen (1992). I.e. as the impact of a change in a structured parameter in the PM has no impact on the product properties, no system dependence exists.

The systems dependencies are further complicated by the accumulation of deviations. Through accumulation, insignificant deviations can be accumulated into global or local system dependencies. E.g. once at the shipyard, the accumulated errors had increased the length of the ship with only 6 cm above the given norms for pacing the Panama channel. The implication of this was that the ship had to be shortened. In this case, the changes were restricted locally at the stern with no major impacts on the ship. Otherwise, this could have been an expensive affair after the ship was build. Also, a number of deviations that individually would have been local system deviation can have global effect on the system. Hence, recording product state is important to prevent unexpected systems dependencies in occurring.

Monitoring product state has several aspects. Firstly, it should be considered whether or not it is feasible to measure (and collect) the data from the shop floor. Secondly, it should be considered whether or not a deviation is of importance to the systems dependencies.

	Deviation		
Monitorability	**Significant**	**Insignificant, but existing**	**No Deviation**
Monitorable	Provable System Dependency	Possible System Dependency	No System Dependency
Not monitorable	***Non Controllable and Problematic***	***Non Controllable and maybe Problematic***	No System Dependency

Table 2: Categorising and evaluating deviations.

Table 2 identifies the implications of not knowing about a deviation versus the need for acquiring the information. As realised, monitoring should not be performed at parameters that has no significant importance to the overall system.

	Deviation		
Monitorability	**Significant**	**Insignificant, but existing**	**No Deviation**
Monitorable	• Heat input in plates when welding and bending causes shrinkage • Plate cut short • Air bobble in a welded joint • Plate temperature	• Plate adjustments errors • Air Temperature	• Small variations in surface roughness
Not monitorable	• Heat input in plates when welding and bending causes internal stresses	• A little primer coating left on the surface of a plate before welding	• A none-important human error

Table 3: Exemplifying Causes of Deviations According to Table 2.

On the other hand not all parameters are measurable (directly or indirectly). Hence, absent information could be problematic in these situations since the lack of information will hinder corrective actions. In situations where deviations can be identified, these should be evaluated with respect to the overall system dependency.

In situations where deviations can be identified and monitored, this should be evaluated in order to decide appropriate actions. Hence, PM-PSM integration should enable compensation based on identified deviations in product state. The underlying objective of PSM is to use state information to correct future production to fit the realised product. This type of correction may not always be feasible, since the guidelines for correction can not be determined. E.g. correction may be to late or to complex to achieve. Hence, different strategies for correction must be adapted based on the product state evaluation.

	Systems Dependence (SD)		
Correction	**Global**	**Local**	**No SD**
Modify Process	Remodel	Replan	Record State
Modify Product	*Rework*	Rework	Record State

Table 4: Strategies for Production Correction based on State Information.

Table 4 illustrates that different strategies can be adapted based on the cause-effect of a deviation. As indicated, production correction can adapt four different approaches:

- ***Remodel.*** Given feasible correction of a deviation of a parameter in the product model with global system dependence, this change will require a Remodelling of the product model. The Remodelling is in order to verify that the functional properties of this change are in accordance with the specifications of the final product, and in order to reconfigure the PM, e.g. to make the next plate shorter in order to match the longer first plate.
- ***Replan.*** Given the deviation only has a local effect, less radical approaches can be adapted, which does only affect the production specifications. E.g. OSS currently apply robot technology, that include adaptive monitoring and control, where the welding process is corrected based on sensor inputs. Replan should include rescheduling in order to take process delays into consideration.
- ***Record State.*** Given the deviation has no system dependence, the PSM is used to record the current product state. Yet, accumulated deviations may have systems dependence. See later.
- ***Rework.*** If the realised product does not apply to specifications and corrections of future production processes are not possible; the product must be reworked to prevent systems dependencies. Re-work includes taking delays into consideration, hence, rescheduling is required. The extent of the rework depends upon the degree of system dependence, e.g. a global system dependence more resources and time than a local - ceteris paribus.

The three first approaches are entirely based on changing the data of the PM/PSM to accommodate the product state deviations, while the fourth approach include physical compensation of the product. Determining systems dependencies is no trivial task and requires extensive domain knowledge to be built into the PM.

6.1 Conditioning

In this section, the underlying phenomenon of the above-mentioned strategies is identified and given a name, as this is not previously proposed in the literature.

The phenomenon of adjusting the system of the product (parts) and the production processes based on product state deviations is in this research called *Conditioning*. Conditioning has a controlling and deciding effect upon the product regarded. The purpose of conditioning is to avoid accumulation in errors/deviations. The process of conditioning is to achieve a sufficient state of "readiness for use" of the product in downstream production activities.

As the product goes through various production processes, the product state changes during (and between) each process. Hence, corrections of the product or adaptions to the process are required during (or after) each process. Such a sequence of frequent corrections or adaptions is here called *Continuous Conditioning*. A partly automation of the adjustment process may then be labelled *Computer-aided Continuous Conditioning* (CCC).

7. Conclusions

Integration of product lifecycle phases has until now primarily been regarded with respect to integration of downstream activities. However, when upstream feedback loops are investigated, alignment of the different lifecycle phases, in this case design/plan/specification and production must carefully be considered from a knowledge integration point of view. In particular, this leads to the several challenges when alignment of the Product Model and Product State Model is pursued. An identification of critical functional properties must be performed e.g. based on a cost-benefit evaluation.

The intention of introducing PSM is, if possible, to modify the later production processes rather than the realised product. Depending on the causal dependencies, strategies are provided for production correction based on product state information. These Conditioning Strategies demand different levels of integration between the PM and PSM. Deviations with local or no implications on functional properties are relatively trivial to correct while global dependencies may require knowledge integration. However, knowledge integration is a non-trivial task and needs a further attention in the future research.

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Endnotes

[i] When considering information feedback and feed forward, it is important to distinguish between a time-line perspective or a product lifecycle perspective focusing on the individual phases. In this paper the focus is put on the lifecycle perspective. Feeding information from the PSM to the PM is considered as feedback due to that the PM is considered as an output of earlier lifecycle phases.

[ii] Fixed “stops” are placed on the working space. The plates are then pushed up against these stops in order to place them right.

[iii] The Mono Mobile 3D Station (MONMOS) is a 3D co-ordinate measuring system, which is operated by a person. MONMOS is based on theodolites, which measures distance and angles.