A Generic Systems Engineering Method for Concurrent Development of Products and Manufacturing Equipment

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Abstract: Manufacturing is getting more competitive with time due to continuously increasing global competition. Late market introduction decreases the economic lifecycle of products and reduces return on investments. Reconfigurable Manufacturing Systems (RMS) reduce the time to market because the process of equipment configuration is less time consuming than engineering it from scratch. This paper presents a scientific framework, to be applied as an engineering design tool, that is capable of improving the relation between product design and the reconfiguration process of RMS. Not only does it support a cross-domain adjustment and information exchange between product developers and manufacturing engineers, it also adds risk analysis for conscious risk taking in a cyclic development process. The method was applied on an industrial case; concurrent design and manufacturing of an environmentally friendly circuit board for wireless sensors. The method may be considered successful. It will lead to better system architecture of product and production systems at a more competitive cost. Feedback on the development process comes available in the early development stage when the product design is not rooted yet and two-way optimisations are still possible.

Keywords: Reconfigurable Manufacturing System, RMS, Risk modelling, FMEA, Qualitative Analysis, Concurrent Engineering, Agile Manufacturing, Production, Equiplets, Micro, Hybrid, Microsystem

1 Introduction

Increased global competition in manufacturing technology puts pressure on lead times for product design and production engineering. Quickly eroding markets, like markets for high-tech systems and micro-technology, especially require tight scheduling of system development; 'being first' leads to an extended economic lifecycle, better market penetration and higher added value for products, together leading to progressively higher return on investments [1]. By the application of effective methods for systems engineering (engineering design), product design and production development can be executed in parallel instead of sequentially. Modular equipment is currently under developed to not only meet the manufacturing demand of single products but to address product groups [2, 3]. Instead of developing dedicated manufacturing systems for specific needs, Reconfigurable Manufacturing Systems

(RMS) reuse modular parts of existing production equipment as building blocks for new manufacturing systems [4, 5].

Reconfiguration of RMS needs to be planned ahead. New systems can rarely be realised without any engineering efforts. Typically 80-90% of a RMS can be assembled from existing modular parts [6], the rest of the modules needs to be specifically developed. The quality of the new modules is a key indicator. Questionable quality of these modules, caused by hasty engineering efforts, leads to unreliable performance when production is ramped up.

This paper presents a scientific framework, to be applied as a systems engineering tool, that consciously enables a periodic 'Zigzagging' motion between product design and manufacturing engineering. It increases mutual understanding and the effectiveness of negotiation between product- and equipment-engineers. The method is based on the definition of 'Domains' as defined by the 'Axiomatic Design' technique developed by MIT [7, 8].

2 Integral System Engineering in Product Design & Design of Reconfigurable Manufacturing Systems (RMS)

Decomposition of a product- or equipment-design and their definition at sub-levels are not performed in a single complex development effort. Instead, progression is made in successive development cycles. Moments of evaluation, to inventory residing risks in the system, are an essential part of the design loop. This was described for RMS in recent work by a graphical representation of a general development cycle as shown in figure 1 [9].

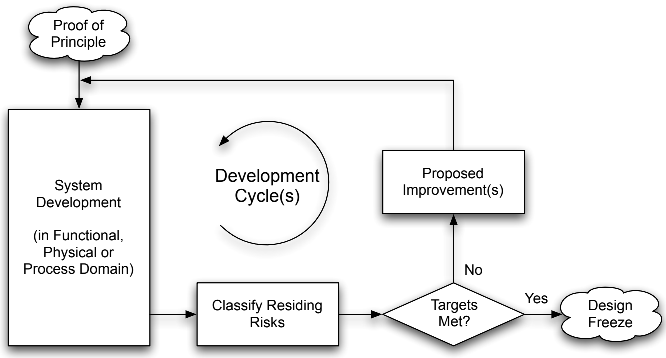

Fig. 1 General Product/Process Development Cycle. The development cycle can be used for the functional, product and/or the process domains

The product/process development cycle describes a 'Development stage', consisting of functional decomposition and analysis at sub-levels, followed by a classification of residing risks. Depending on the outcome of the classification process a corrective action to improve the system is determined and executed. Basically all known design methodologies that have been developed in the past can be used in the development cycle e.g.; proven tools for system development are: QFD, morphological matrices, Pugh matrices. SADT/IDEF0 are typically applied for sequential processes like manufacturing. The classification of residing risks in the system can be done with Failure Mode Effect Analysis (FMEA) or Qualitative Analysis (QA). Suitable applications of the design loop have been described in [6, 9 & 10]. The method has proven to be of good use to the various system design processes but it has problems addressing the different domains concurrently. The method of Axiomatic Design is used to expand the development cycle to enable this.

The Axiomatic Design theory describes the domains and how to connect them. Typically the domains applied are; the functional domain, the physical domain and the process domain. The domains are related as shown in figure 2.

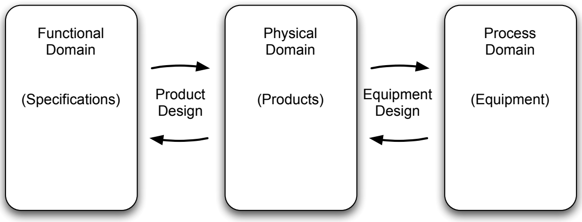

Fig. 2 Relational mapping of the domains. Specifications in the functional domain are brought into relation to design parameters of a product in the physical domain by the product design process. The design parameters are related to the process domain by the equipment design process

At the start of a project, the functional requirements are decomposed in levels, thus dividing the project into smaller parts that can be better understood. The decomposition simultaneously takes place for the other domains to fortify the concurrent character of the development process. This process is called zigzagging [8]. Figure 3 shows the process of zigzagging in the relational map of figure 2. Zigzagging aims for a cross-domain harmonisation of the requirements, product design and equipment. The amount of remaining work is broken down and equally optimised over the domains. For the remaining project risks, a conformable breakdown should be obtained.

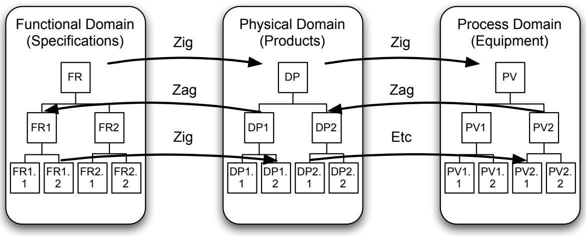

Fig. 3 While zigzagging, a hierarchical descent is made in the design process for as well specification, product design and production means. It leads to simultaneous decomposition of all domains

However, relations between the domains should be modelled by an appropriate method of system engineering. In practice, as explained above, these methods are dependent on the domains and therefore not the same for product and equipment design. Due to this incompatibility, the process of zigzagging is not automatically congruent with the cyclic development procedure. The development cycle is not able to address all domains at the same time. Different cycles should be adjusted in some way to align the concurrent procedures and synchronise design processes in simultaneous development cycles. Since decomposition, definition at sub-levels, and risk analysis are performed in a different manner, the monitoring stage 'targets met', basically a Boolean indicator, will be the most suitable stage to compare the remaining project risks. The risk classification outcome typically is a measure that can be prioritised. This enables comparison with different risk-analysis-techniques, such as FMEA or QA. So for an improved development cycle, that is capable to support more than a single domain, the outcome of the risk classification stage is compared across the domains. This was implemented as shown in figure 4. The improved 'Multi Domain Development Cycle' was applied on an industrial case for testing.

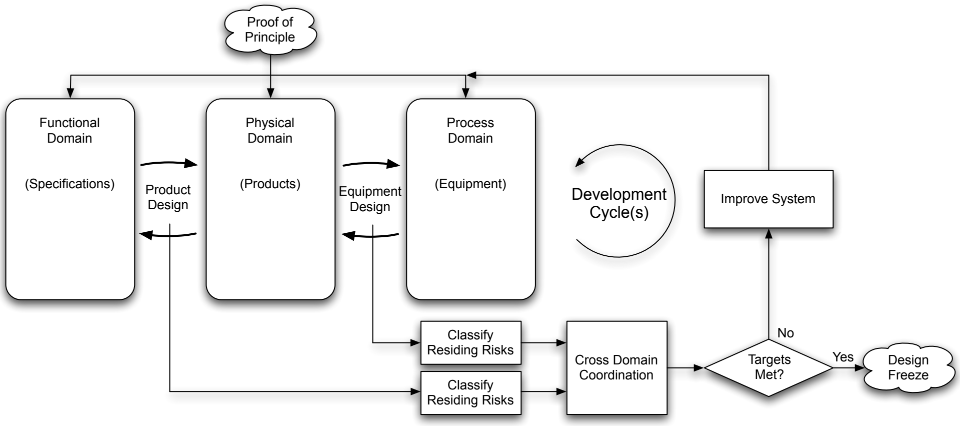

Fig. 4 Multi Domain Development Cycle for cross-domain coordination. The risk classification results from product design and equipment engineering processes are taken into general consideration. Joint classification if targets are met and what to do to fulfil them in the next cycle are point of discussion before definition of improvements. Struggles for engineers are administered and equally divided

3 Case: Manufacturing of an Environmentally Friendly Circuit Board

3.1 Definition of the Product

The applied case, manufacturing of an environmentally friendly wireless sensor system, consists of a fairly simple electronic circuit that has to be realised in large quantities. Due to the fact that most wireless sensor systems cannot be recycled at the end of their life cycle, the aim is to minimise the environmental footprint of these sensors when disposed. This is done i.a. by replacing the standard printed circuit board with an environmentally friendly alternative (figure 5). This circuit board is embossed in a biodegradable plastic using a carbon paste to realise conductive tracks [11]. The circuit board, as required for this case, introduces a number of new features. First, the electronic layout is embossed in a plastic part, secondly, the part is filled with a carbon paste to create the conductive tracks. The electronic parts are placed in the carbon paste prior to curing. A regular pick & place process is applied.

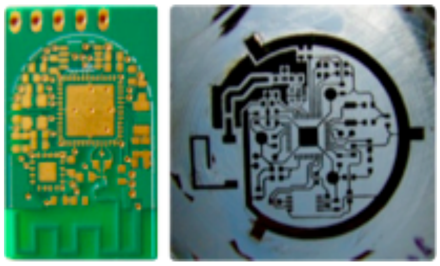

Fig. 5 Left, printed circuit board of a wireless sensor system.
Right, circuit board made of bio degradable PET

After curing, the circuit is electrically functional and can undergo further mechanical assembly. The paper focusses on the design modifications of the plastic part in which the circuit is embossed in relation to its manufacturing process. The manufacturing process is to be implemented as a modular and reusable part of an RMS.

3.2 Application of the Multi Domain Development Cycle in a Design for Manufacturing Process

First, the state of the art PCB integration was compared to the envisioned embossed circuit board using a concept selection matrix (also known as Pugh's alternate technology matrix). Parallel to this analysis, SADT was applied on the product flow through the RMS; the most significant risks were determined. Based on the outcome of the Pugh matrix and the SADT, the cross-domain negotiations were executed and follow-up actions for the product and production development processes were defined.

This procedure was repeated in three stages in which product and process development were put in sync. The full analysis is given in figure 6. After completion, a solution was found that matched the goals of the product designers as well as the manufacturing engineers. The iterative process was cycled for three times in total. A result was found that satisfied the goals of the product designers as well as the manufacturing engineers.

4 Discussion and Conclusions

4.1 Design Information Flow when Concurrently Applying the Development Optimisation Cycle

The systems engineering cycle, as proposed in this paper, was successfully applied to the development of a new method for lens stack-alignment and its manufacturing equipment. The question arises if this could also have been the case if this method had not been applied. Processes of industrialisation for hybrid micro systems are diverse and involve large investments. This makes an objective reference measurement expensive and heterogeneous. What can be concluded is:

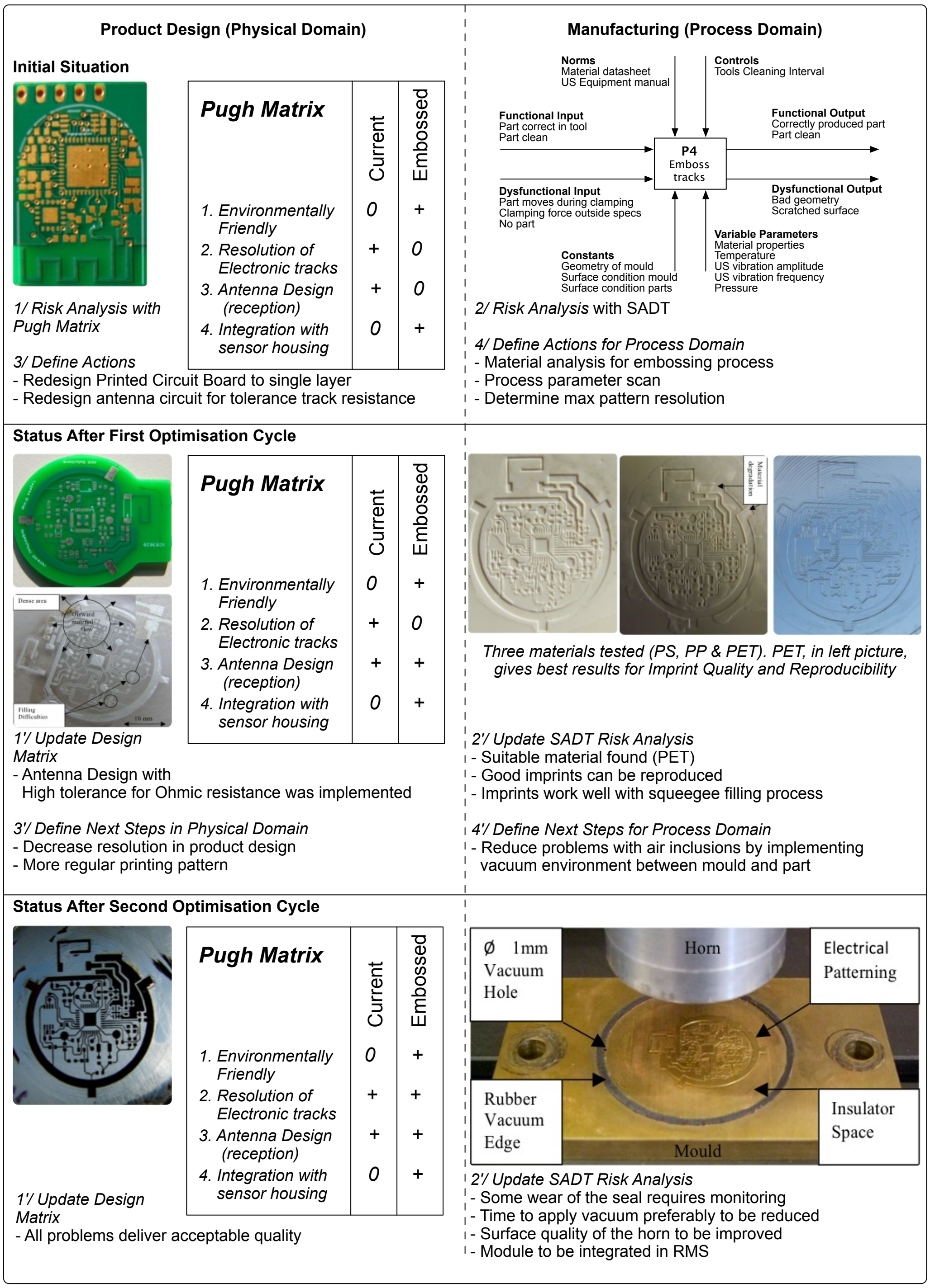

Fig. 6 The Multi Domain Development Cycle in three consecutive steps

At first, the method organises the design process of product design and manufacturing equipment. It monitors functional progression in development. This addresses development risks in an optimal order, structurally reducing the hazards of project delay. Further engineering may be considered to be 'work' instead of 'investigation' leaving minimal risks left.

Secondly, the optimisation cycle implements a zigzagging motion between the functional, physical and process domains. All domains will be decomposed hierarchically and consecutively defined at the various sublevels. This is conforming the definition of concurrent engineering in the axiomatic domain [12]. Communication between the domains is greatly enhanced as ideally proposed in the Axiomatic framework. This is shown in figure 7.

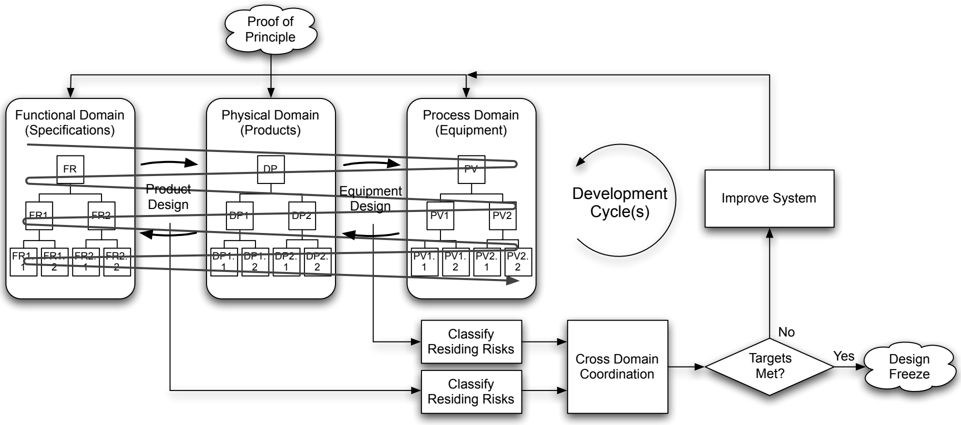

Fig. 7 Zigzagging through the domains. Decomposition and definition evolve concurrently

Thirdly, the risk inventory is updated with a regular frequency. This enables a continuously updated view on the remaining project risks. The most dominant risks can be addressed in a forehanded way, by timely prioritising the largest risks and pulling them forward in time.

Finally, the staged visualisation of project risks will elevate the level of communication in the organisation, widening the scope of personnel to be addressed. Though the engineers profit by an overview of remaining project risks, the higher level of management will also be capable of understanding the project status. This reduces discrepancy in the estimates of perceived effort to complete the project; less explanation to the management is needed.

These four effects together lead to a quicker and more structured optimisation of problems in the concurrent design of products and equipment. Visualisation of progression in development, the appropriate feedback cycle and the improved communication with technological and operational management will lead to a better architecture of product and production means at a more competitive cost.

The method as described in this paper, although applied for RMS, is truly generic and can be used for the analysis of a diversity of processes in the development and engineering stadium. The method is flexible due to the ability to fit domain specific tools for analysis in the development cycle.

4.2 Conclusion.

The RMS Optimisation Cycle, combining SADT and an improvement cycle with a layered structure, can be successfully applied to monitor development of RMS. Visualisation of development-progression, the appropriate feedback loop and the improved communication with technological and operational management, will lead to a better system architecture of product and production means at a more competitive cost. The results come available in the early stage of development when the product design is not rooted yet and combined optimisations are still possible.

Acknowledgements

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