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A METHOD FOR INDEXING AXIOMATIC INDEPENDENCE APPLIED TO RECONFIGURABLE MANUFACTURING SYSTEMS

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ABSTRACT

Modern manufacturing has to deal with global competition, in which customers have high purchasing power. Production efficiency and rapid response to customer demand are dominant conditions for enterprises to stay successful. Reconfigurable Manufacturing Systems (RMSs) are designed to have a modular architecture in both mechanical design and control system. The architecture enables change of the machine structure quickly, by adding and removing parts of the system, and by changing the corresponding software programming. It can handle short times to market. This paper presents an 'Index-Method' to monitor the reconfiguration of RMS. The method is able to categorise the reconfiguration and related development in seven stages. It focusses specifically on the Independence Axiom. The main goal is to find all relevant parameters to cause interactions, and to decouple them. The solution, aiming to be scientifically vigorous and practically applicable, was applied to a true case; the development of a manufacturing system for an inkjet print head for industrial applications. The realisation of the system required the development of new process technology. The index-method may be considered successful. It has the ability to structure the configuration process of RMSs. The method harmonises well with the industry known V-model.

Keywords: reconfigurable manufacturing systems, Axiomatic Design, Independence Axiom, structured analysis design technique, qualitative modelling and analysis of processes, V-Model, RMS, SADT, QMAP.

1 INTRODUCTION

Modern manufacturing enterprises have to compete in a global economy. Global competition increases the purchasing power of customers. It enlarges the dynamics with which manufacturing enterprises have to deal. The arena is highly competitive; high production efficiency and rapid response to changing customer demand are dominant conditions for enterprises to stay successful [Koren, 2006]. This has led to adjustments in production processes, production approach and applied equipment. Manufacturing has become 'agile'. Production locations and manufacturing equipment have become modular and subject to evolve frequently and on short notice. This is the venue of 'Reconfigurable Manufacturing Systems' (RMSs) [Gunasekaran, 2001; Puik, 2010].

RMSs are a logical addition to 'Dedicated Manufacturing Systems' (DMSs) and 'Flexible Manufacturing Systems' (FMSs). DMSs are most traditional; they are applied for a long period of manufacturing without significant changes, even up to 30 years. FMSs are computer numerically controlled systems. In FMSs, the application of computerised control systems enables fast adaptions to a range of variations in production. The structure of the machine, however, was determined by the mechanical system design and is not able to change. RMSs fill the gap by adding a modular architecture in both mechanical design and control system. The architecture enables change of the machine structure quickly by adding and removing parts of the system, and by changing the corresponding software programming [Moergestel, 2011]. The core characteristics of the RMSs are: modularity, integrability, customisation, scalability, convertibility, and diagnosability. RMSs therefore are responsive manufacturing solutions whose production capacity is adjustable to fluctuations in market demand and whose functionality is adaptable to new products [Koren, 1999]. The re-configuration of RMSs takes from hours up to some months, depending on if the change can be implemented by the application of existing process-modules or if new modules have to be developed. Especially in this last situation, there is a desire to closely follow the development of the new process-modules, since their development largely determines the critical path of the total manufacturing solution. The increased attention focuses on the mechanical- and software design of the modules, initial testing of these modules and the improvements required to bring the level of the new modules up to the desired standard.

This paper presents an 'Index-Method' to monitor the development of new process-modules and their interaction with other (existing) modules. The method is able to categorise the development of reconfigurable modules in seven stages, from 'functional definition' to 'product accepted'. The index-method focusses specifically on the Independence Axiom. The main goal is to find all relevant parameters to cause interactions and to decouple them. The solution is aiming to be scientifically vigorous as well as practically applicable.

2 METHODS FOR MONITORING DEVELOPMENT PROGRESS OF RMS

A range of systems engineering tools, which have been defined in literature, could be applied to monitor the reconfiguration of RMSs. The following paragraphs inventory the most successful tools today. Most of these tools are actually applied in industry for monitoring the progress in development of RMSs, eventually in a concurrent way.

2.1 Tools for the Conceptual Design Phase

The Structured Analysis Design Technique (SADT) was originally developed for software development but appeared to have a much broader application area [Ross, 1977]. For manufacturing purposes, SADT has been refined to focus on errors that tend to inherit through subsequent process steps. This method is called Qualitative Modelling and Analysis of Processes (QMAP) [Brands, 2000; Bullema, 1998]. Structured analysis methods, either SADT or QMAP, can be applied when no hardware is available yet. This makes these methods particularly suitable for the early stage of development. The combination of SADT and Axiomatic Design (AD) has been applied before on manufacturing systems [Triki, 2011], however, this study optimises equipment occupation ratio. There is no focus on FMSs or RMSs.

Quality Function Deployment is a value-engineering tool usually applied for mapping customers' wishes in relation to a product design. It uses a layered approach to deploy function to lower product levels e.g. subsystems and parts [Akao, 2004]. All methods, SADT/QMAP and QFD have proven to be useful in the early phase of product/process development and have, successfully been combined with Axiomatic Design methods [Triki, 2011; Kim, 1991; Buseif, 2006].

2.2 Risk Analysis Methodologies

Parallel to the structured design techniques, which pull development risks forward in time when developing RMSs, industry frequently applies 'risk analysis' tools. During early development, risk plotting in Maturity Grids (MG) seems favourite. During the engineering phase, the Failure Mode Effect Analysis (FMEA) may be considered the most popular method [Hassan, 2010; Werdich, 2011; Puik, 2013]. Many variations of these basic tools apply.

2.3 Statistical Performance Monitoring

Industry usually determines the performance of manufacturing systems by measurement of the 'Production Yield' (Yp). Yp is calculated by dividing 'the number of products produced with all functional requirements successfully met', by 'the total number of products produced'. Depending on the applied philosophy about manufacturing, usually an enterprise standard, the production yield is applied for process improvement using a statistical set of tools and strategies e.g.: 'Six Sigma' analysis as developed by Motorola, 'Design of Experiments' DoE' by Taguchi or an arbitrary process capability index. Since all methods are based on statistical input, determination of full maturity should take place on a sample set of products taken from pilot- or actual production. Statistical production information is a reliable and generally well-accepted measure but it also has its downside. In the early development phase, little statistical information is available because the new production modules have not been realised yet. Their only existence may be in CAD systems or even in the developers' heads. At this stage, Statistical information is of no use for an index-strategy for RMS modular building bricks. Therefore, statistical production information is considered to be of great use as a verification tool for the absolute state of quality, but only during the engineering stage of the development.

2.4 General System Engineering Tools

Maturity, or the state of reaching full development in design and manufacturing of products, is in literature mainly investigated using the Capability Maturity Model (CMM) [Bate, 1995; Dooley, 2001; Fraser, 2002; Team, 2002; Ren, 2004; Shah, 2009]. CMM uses five stages to define maturity and its progress, but is mainly used from an organisational perspective rather than a technological perspective. This makes CMM rather unsuitable to follow the development progress of RMSs during its development. A technologically driven approach uses a quantitative way of calculating product maturity by indicators [Tekcan, 2010]. However, this method strongly depends on statistical process data, and its indicators are unsuitable for the early design stage where systems only partially have been realised yet.

2.5 V-Model and Waterfall-Model

The 'V-model' is a modified and optimised version of the 'Waterfall-model'. Both methods, originated for software development, are graphical representations of the systems development lifecycle [Royce, 1970; Friedrich, 2009].

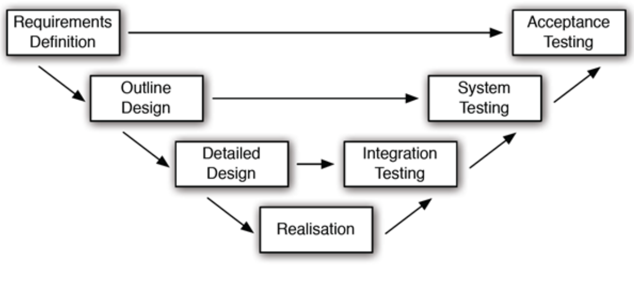


Figure 1: The V-Model may be currently be seen as an industry standard, but many versions apply and implementations differ.

The main steps to be taken in conjunction with the corresponding deliverables are summarised in a validation framework. This is done in a sequential process (Figure 1). The V-model focuses on testing more than the waterfall model. Both models are indicating the 'actions to be taken' more that defining the 'state of the product'. Interpretation of the V-model differs in literature and practice. Though the V-model has been presented over 30 years ago, discussion is still active and variations of the model are still being developed [Suh, 1999; Suh, 2000; Christie, 2008].

3 INDEXING THE INDEPENDENCE AXIOM

3.1 COMBINING SYSTEM ENGINEERING TOOLS

The method for indexing RMSs is based on a combination of three systems engineering methods. The first one is the SADT, in the QMAP layout, as it is more suitable for manufacturing purposes. It will further be referred to as SADT. The second is the application of AD and its decoupling strategy of design matrices. Thirdly, to finally index the progress on reconfiguration of the RMS, a qualitative analysis based on coding is used. This enables the index-process to use discrete and clearly defined steps to monitor progress. It integrates in good harmony with the V-Model.

The index-process focuses on the Independence Axiom; it follows the development of the RMS from definition up to the point where the system is fully decoupled [Suh, 1990; Suh, 1999]. The method uses the design matrices, starting with the design equations according to good AD practice

$$\{FR\} = [A] \cdot \{DP\} \qquad (1)$$

$$\{DP\} = [B] \cdot \{PV\} \qquad (2)$$

where [A] & [B] are the product- and process-design matrices that respectively connect functional requirements (FRs) to design parameters (DPs) and design parameters to process variables (PV). If a product design has three FRs and three DPs, the product design matrix would have the following form

$$[A] = \begin{Bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{Bmatrix} \qquad (3)$$

and decoupling would be successful if the matrix is diagonal or triangular. However, in order being able to draw the design matrix, all elements of the matrix should be known. This means that all product- and process-design equations are fully understood as well. This can be a laboured task since the design matrices provide no feedback if parameters are missing in the process. Therefore, the index-method as described here focuses on three challenges:

- Finding a full set of design equations and making sure there are no missing elements in the design matrices;
- Uncoupling or decoupling the matrix;
- Structural scanning the operating windows of the RMS to verify (or guarantee) that no elements of the design matrices were missed.

The first item is covered by the application of structural analysis, in this case SADT. The second item is covered by the decoupling progress of the axiomatic design matrices. The last item is addressed by performing an endurance test with characterised input parts.

Typically, at the definition stage of the RMS, the product design has been determined up to a large extent, however, not completely. This means that the FRs are known, the DPs are partially known and the matrix [A] is not stable. SADT describes the manufacturing process in a layered hierarchical structure. By this approach, it breaks down the manufacturing process in hierarchical levels that match the modular structure of the RMS (Figure 2). A top down decomposition of the production flow in 'Data-Diagrams' is interchanged with the breakdown of the production flow in elementary process actions. The typical hierarchical structure for an RMS is: 'Line-Cell-Module-Device'. As such, the analysis presents all modular building blocks needed to configure the production system.

Decomposition is typically done with a 'zigzagging' motion through the domains (FR, DP, & PV) to deal with constraints in the design at the lower hierarchical levels. Instead of defining and meeting all FRs before moving to the DPs, first all FRs, DPs & PVs at the highest level are defined before descending to the next level.

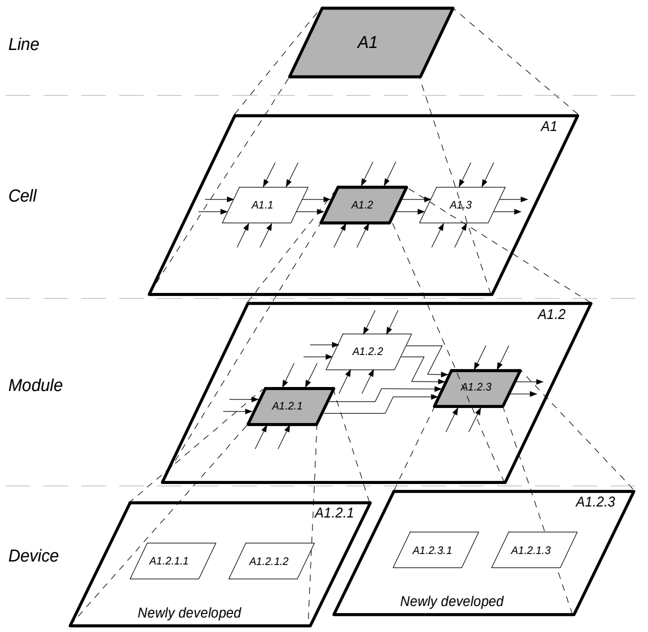


Figure 2: Top down structure of the SADT data-diagram. In a layered structure of Manufacturing-'Lines', 'Cells', 'Modules' and 'Devices', the structure is decomposed to enable determination which modular parts can be reused or require new development. Changes escalate from bottom to top.

During the reconfiguration process, the realisation of new modules and devices, to comply with a new manufacturing process, can require substantial research efforts. The modules and devices can be a) completely reused from earlier design, b) altered from earlier systems, or c) built up from the ground. For all three situations, the output of the data-diagram plots the impact to the process of reconfiguration of the RMS. Basic process-functionalities are described using an 'Activity-Model' (Figure 3). The activity-model uses parameters to describe functionality of the particular function.

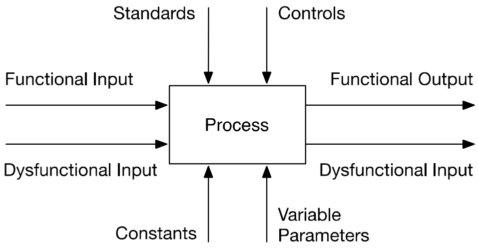


Figure 3: SADT/QMAP activity-model.

Input parameters, can be 'functional' or binding characteristics of a good product at start, or 'dysfunctional' representing potential hazards or errors of the product before the particular process has even started. Conditional input parameters, like 'norms and controls' reflect boundary conditions or demands of the process. Parameters related to the transformation mechanism, comprising of 'constants and variables', are representing the process or equipment characteristics. All input parameters serve as determinants for the output parameters, again functional or dysfunctional.

The SADT analysis presents a total overview of the reconfiguration process of RMSs since its hierarchy and process steps are visualised in detail: a) It confronts the engineers with the logistic, but also the functional layout of the system. b) The SADT procedure decomposes system functions when moving from data-level to activity-model. During this stage, not only the modules are defined, but also their interfaces, both physical as functional. c) The general system architecture is finalised with the completion of data-diagram and activity-model of the SADT analysis, having defined all building blocks.

SADT, being a singe domain analysis, needs to be performed for each domain separately. However, SADT and derived tools are most effective for sequential processes. In the product domain, to find FRs and DPs, QFD might be the more obvious choice. Both tools can be combined in good harmony.

Execution of the SADT and/or QFD analysis is done by a diverse group of engineers. The participants have different backgrounds, from product- and manufacturing engineering and even service operations. The level of experience of the participants varies from junior+, as it appears hard to contribute from the entry level of engineering, to senior.

3.2 Towards an Index-Method for RMSs

The outcome of the SADT analysis will serve as the basis for the first two index-levels to enable tracking the reconfiguration process of the RMS. The index-process is qualitatively coded from -3 to +3 to provide a match with the in industry widely accepted V-model, starting with

- Level -3; Product or process hierarchy is not completely known yet. This corresponds with not having completed the SADT analysis at data-level;
- Level -2; Product or process hierarchy has been determined, but parameters have not. This level corresponds with a completed SADT at data-level but no completion of the activity-level.

Axiomatic Design matrices provide the input for the successive levels '-1' and '0'. The elements of the design matrix are subtracted from the parameters of the analysis at SADT activity-level. Figure 4 shows the gathering of elements in the process-design matrix [B]. In parallel, matrix [A] will be updated as well to get a complete set of design matrices. It will serve as obligatory condition for the next index-level. The statuses of the elements are indicated as respectively '?', 'X' and '0', being 'Unknown', 'Relevant' and 'Not Relevant'. Optionally, the small 'x' may be used without consequence for 'Somewhat Relevant'.

- Level -1; Both levels of the SADT analysis have been completed, elements of the design matrices have been gathered to form a complete set of design matrices ([A] & [B] are known at all hierarchical levels).

Whereas the elements of the process-design matrices have been gathered, the next step is to satisfy the Independence Axiom. An independent design requires the design matrices to be diagonalised or triangulated. This process, requiring structural understanding of the design and production methods, leads to an uncoupled (diagonal) or decoupled (triangular) process design.

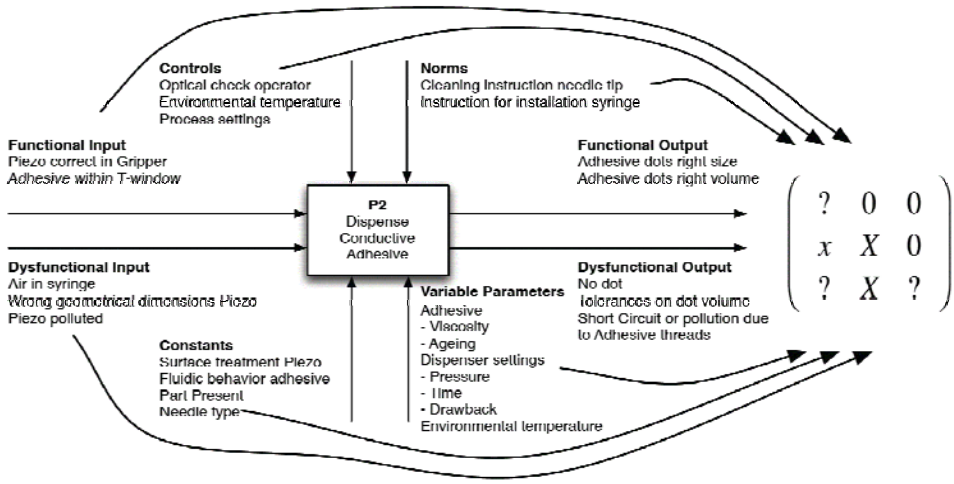


Figure 4: Application of the design matrices for quantification of the independence measure. Data is extracted from the SADT activity-model.

Due to the fact that the SADT data-level has introduced a layered hierarchical structure, not al process-design matrices will be optimised simultaneously. The optimisation process starts at the highest level (Cell & Line, Figure 2) and works its way down to the bottom-level (Module & Device). Once this process is completed, all parameters are known. Process design matrices are defined and uncoupled or decoupled, represented by diagonal or triangular design matrices. If this is the case, the design axiom may be considered satisfied. All information to realise construction, hardware- and software-controls is gathered. The physical realisation process of the system may be finalised. Based on the completion process of the Axiomatic Design matrix, the next Index-level is defined as

- Level 0; Completed SADT and parameters in matrix, all levels uncoupled or decoupled. Systems & sub-systems have been realised.

3.3 Ascertain Matrix Elements by Testing

At this point, the index-process has not yet been completed. The reason for this is that certainty of all elements of the design matrices being found cannot be guaranteed. Forgotten elements of the matrix could show up during late engineering work or even in the field when the product has been released. This effect could occur due to the fact that properties, which always stayed within a narrow margin, start altering due to unforeseen changes in construction, materials or structure. Though this effect cannot be excluded completely, the risk of similar occurrences can be minimised by applying testing over the full specified operating conditions. Therefore, the index-method is elongated with a practice tests in a realistic environment, with realistic parts and tools up to the level of factory- and site-acceptance-testing (FAT & SAT).

- Level 1; Sub-system testing has been completed successfully;
- Level 2; Full system test, successful FAT & SAT (Relation FR→DP→PV at all hierarchical levels).

3.4 Acceptance Testing

The last step is optional for RMSs, but completes the index-method up the level of customer satisfaction. Once the production is running well, PVs, FRs & DPs are satisfied but it does not automatically mean that the end-customer is satisfied too. A satisfied customer does not only find the FRs within specs but also the 'customer attributes' (CA, the specific expectance towards the product by the customer). This step may be considered as the ultimate level of verification. It is optional for the development of RMSs, since production engineers usually get the functional specifications as a starting point. However, it completes the index-method to enable verification for product designers and marketeers as well.

- Level 3; Customer satisfaction: customer perception matrix was successfully verified (Relation CA→FR).

3.5 Overview of the Independence Index-Method for RMS

The development of RMSs, and specifically new production modules to be used for RMSs, has been categorised in a number of seven stages as shown in Figure 5. The development progress is monitored from left to right.

Each completed level is a milestone in the configuration process. This does not mean that completion of a level is a binding condition to start working on successive stages. However, the true level of development, e.g. as reported to the management, does never exceed the last completed stage.

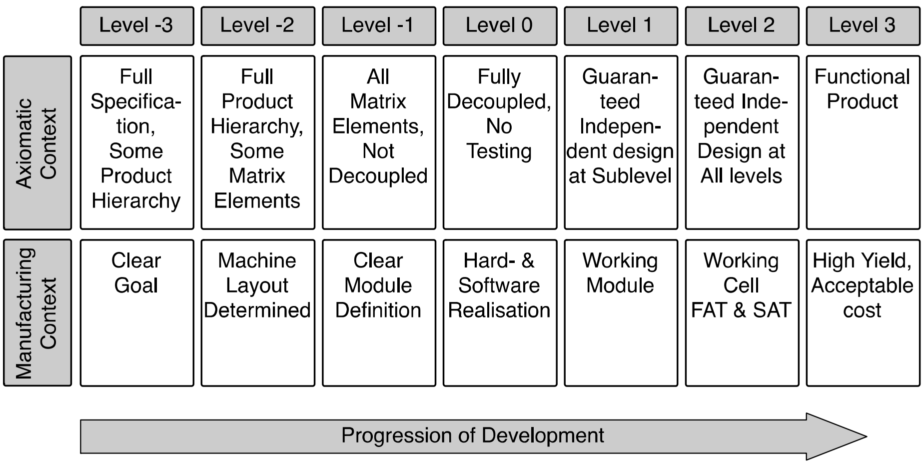


Figure 5: Development of an RMS in seven steps from the embryonic stage to a complete and independent design. Levels are analogue to the progress of the axiomatic independence of the product- and production-design.

4 CASE STUDY; ASSEMBLY OF INKJET PRINT HEADS

4.1 DEFINITION OF THE PRODUCT

The applied case concerns the manufacturing of an inkjet print head for industrial applications. The total manufacturing process consists of over twenty fabrication steps, most of them performed within a modular manufacturing framework. The manufacturing step, which was selected for the analysis of the index-method, required the development of new process technology. This process concerned the bonding of a thin plastic foil onto an injection moulded base assembly of the print head, consisting of several parts. The print head is shown in Figure 6.

The equipment integrator had the availability of a state of the art equipment framework, consisting of a cell concept with a library of functional process modules, applied and tested in the past. Bonding thin foils under these circumstances, however, was considered a new process that required a new gripping device and a new process module.

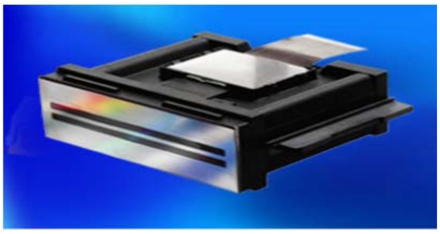


Figure 6: The print head has been pre-assembled from a number of parts. The foil is to be bonded to the lateral side of the channelled structure.

The required assembly process, at the start of the configuration, was tested up to some extent. The process had been performed, using manually operated assembly tools, which required a high level of craftsmanship. So far, the quality of the adhesive bonds had been of moderate quality.

The status at start of the process development: a) all FRs of the print head had been defined in detail; b) DPs had been determined, but up to less extent and may not be complete; c) PVs had not been defined at all.

4.2 APPLICATION OF THE INDEX-METHOD TO INKJET ASSEMBLY

The development of a new process-module and the integration process into the reconfigurable manufacturing framework is described and visualised from stage to stage in Figure 7. Since manually operated tools only had provided moderate product quality, an overhaul of the assembly process was inventoried at the earliest design stage. A number of shortcomings were found in the manually operated tools during initial analysis. To correct for the imperfections, the mechanism for alignment, mating and clamping the part needed considerable change, which in its turn introduced extra risks in the development. A test setup for the modified process was realised to address the risks, again manually operated but with a totally new assembly core. This setup was tested to assure full decoupling. Next, the assembly core was copied into the newly designed process module and verified for operation at the successive hierarchical levels. Step to step details are found in Figure 7.

5 DISCUSSION

The index-process to monitor configuration of an RMS for an inkjet assembly problem was considered successful. The question arises what would have been the result if indexing had not been applied. Processes for industrialisation of miniaturised hybrid systems are diverse and involve large investments. This makes an objective reference measurement expensive and heterogeneous.

5.1 SATISFYING THE INDEPENDENCE AXIOM

What can be concluded is that well-configured RMSs fully satisfy the Independence Axiom and that the process of configuration benefits from a well-structured approach towards this state. The index-method as described in this paper maximises the chances of successfully meeting the Independence Axiom for the following reasons:

At first, it maximises the chances of missing matrix elements being found, satisfying the Independence Axiom and the process of decoupling have been described extensively in literature. However, guarantee of having found all matrix elements is still a significant problem in industrial practice. Note that missing matrix elements are destructive to the decoupling process. Pulling the decoupling process forward towards the project start, by applying SADT, helps finding many parameters that can be transferred to the design matrices, but is no total guarantee that all matrix elements are actually found. Elongating the decoupling process backwards, by scanning operating windows and endurance testing, increases chances of missing matrix elements being found substantially. The combination of SADT and testing is in every way the most optimal situation.

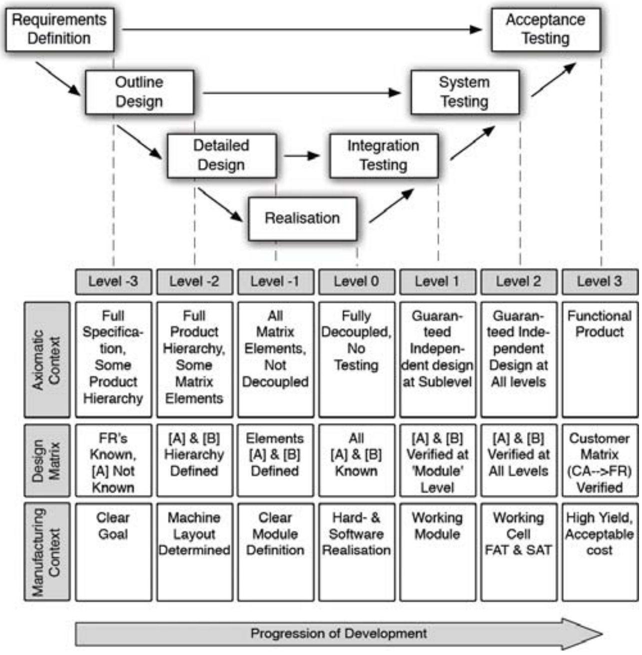


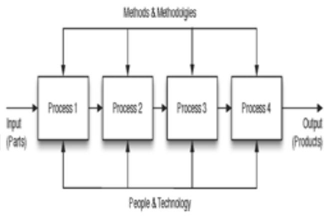
Figure 8: Development of RMSs in six steps from the embryonic stage to a complete and independent design. Progress again monitored from left to right.

Functional Requirements Known → ***Index level -3:*** *Full Specification, No Hierarchy*

Actions Taken

- A group of developers and engineers were asked to form a vision on the production process of mounting thin foils to the fragile printhead;
- A standard Pick&Place process was proposed. The process was decomposed using the SADT analysis in elementary steps;
- The process-steps, handling, dispensing, joining etc. appeared available in the companies process-library, except for one process; the equal distribution of bonding forces between foil and printhead. A novel system for applying an equal pressure needed to be developed;
- All other process modules were considered to be available and applicable with minor risks.

Result: Systems Specification at SADT Data Level

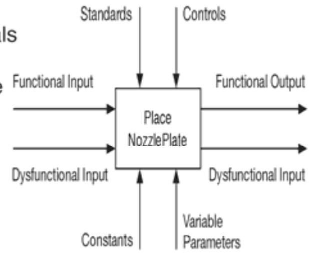


→ ***Index level -2:*** *Full Hierarchy, No Parameters*

Actions Taken

- The process of applying an equal force was analyzed using the SADT Activity Model. This reveals an extensive amount of parameters;
- Preliminary investigations, desk research but also laboratory tests, were performed to determine the sensitivities of Process Variables (PV's) to Design Parameters (DP's) (formula (2), matrix [B]).
- Big X's and small x's are determined. Non-relevant parameters were skipped;
- Structure of the process-module was determined, functional design completed;
- The process was reviewed by middle management and (optionally) with external experts to minimize the chances of missing parameters being undefined.

Result: Systems Specification with SADT Activity Model, as complete as possible

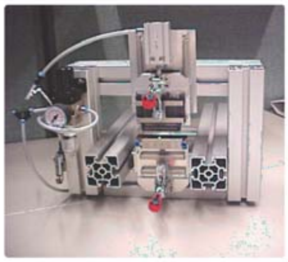


→ ***Index level -1:*** *All Parameters, No Decoupling*

Actions Taken

- A test setup with full functionality was made to test interactions at process-module level;
- Laboratory tests were performed and sensitivities in the [B] matrix were completed and confirmed;
- Error analysis was performed based on the weaknesses as defined in the SADT Activity Model;
- Operational range of PV's and their tolerances were measured;
- The design Matrices up to the 'Module-Level' were fully decoupled (if not yet the case);
- The final module was designed and realised, based on the functional solution of the test setup;
- Tests on the completed module were done to verify the operational functionality;
- Produced parts were investigated on their production quality.

Result: Functioning, fully uncoupled or decoupled Process Module(s)



→ ***Index level -0:*** *Decoupled System, No testing*

Actions Taken

- This is the actual configuration stage of the RMS: All process-modules were integrated to form a total solution for the manufacturing assignment; the newly developed module was combined with proven modules form the past, control software was finalised;
- Interactions between the modules were tested te ensure full decoupling at al levels;
- An internal Factory Acceptance Test (FAT) was performed and results reported to management:
  - Initial tests on the full system to verify the operational functionality in terms of manufacturing quality and speed;
  - Produced parts were investigated on their production quality.

Result: Fully integrated and decoupled manufacturing system

→ ***Index level -1:*** *Subsystems Tested, No System Test*

Actions Taken

- A test batch with the size of a daily production was prepared, parts were characterized for geometry and material properties. Parts were sorted in critical combinations of tolerance, and tested in the production system. Rest of the parts (75%) was tested in an endurance test (SAT);
- The internal Site Acceptance Test was performed and results were reported to management:
  - Initial tests on the full system were performed in order to verify operational functionality in terms of manufacturing quality and speed;
  - Produced parts were investigated on their production quality;
- The system was moved from the reconfiguration area to the production area in the factory.

Result: Tested system, acceptable manufacturing performance (speed&yield) for pilot and ramp-up.

→ ***Indexlevel 2:*** *System Tested* → ***Start Pilot Production***

Figure 7: Configuration Process of a Manufacturing Solution for Bonding Thin Foils in Inkjet Systems.

Maximising the chances of finding all matrix elements is a typical strength for the V-model, because it structurally connects the design process with testing of the final design solution. Figure 8 shows the match between the index-method and the V-model. Where the V-model describes the actions that need to be taken, the index-method describes the condition that should be met before a certain level may be considered complete.

Secondly, the axiomatic design technique introduces a zigzagging motion that compensates for a significant weakness of as well the V-model as SADT. These methodologies tend to struggle with changing specifications. This is also the case if changes need to be made in the product specifications, during the development of processes; this is a recurrent problem for RMSs when the product design needs to be changed in order to reduce complexity of manufacturing equipment. Zigzagging starts at the highest hierarchical level and goes down through the lower levels till realisation starts. In the second half of the V-model, zigzagging is performed again, but in opposite direction, going back up to the highest system level again (Figure 9).

Thirdly, the index-method is fairly simple to implement and connects to the existing level of industrial knowledge. It increases awareness in finding matrix elements and the decoupling process. Together with the V-model it not only monitors the progress of development, but it also defines the next actions to take. The designers have a paved path to follow.

The combination of these three effects will lead to a well-structured and thorough analysis of product and production means to satisfy the Independence Axiom. This in its turn will lead to a better system architecture of as well product and production means at a more competitive cost.

Level 0 indicates the moment where investments in equipment start to increase rapidly. In practice, flexibility decreases at the same pace as investments go up. Negative indices clearly indicate that decomposition has not been completed yet, positive indices indicate that hard- and software have been realised but that testing is still in progress. As such, estimation can be made of the (financial) impact of considered changes and how to reduce them to managerial and technological consequences.

In general management, the V-model is usually well understood. Axiomatic design and the axiomatic index-levels, as defined here, are practical tools for design- and system-engineers. The model has the ability to connect the managerial framework of thinking to the world of engineers, leading to better understanding of both parties in the organisation.

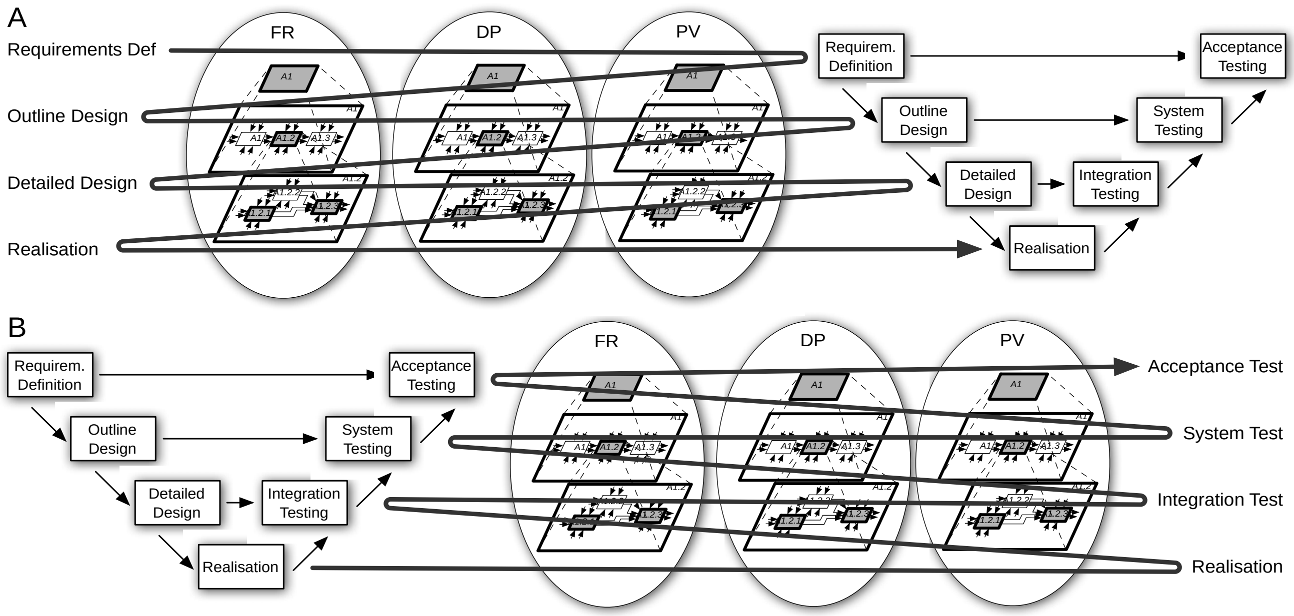


Figure 9A: Zigzagging motion within the hierarchical descent of the V-model to recursively connect domains. Figure 9B: During testing the zigzagging direction is reversed and hierarchically moving up again.

6 CONCLUSION

The index-method to monitor the progress in satisfaction of the Independence Axiom has the ability to structure the configuration process of RMSs. The method combines well with the industry known V-Model and closes the gap to the operational management. The method was successfully applied to monitor and optimise an industrial case. In this paper, the investigations were focussing on RMSs, but the method may be applicable in a broader range of situations where monitoring development progress is needed.

7 FUTURE WORK

The index-method, as described here, was developed for- and applied to RMSs. The method is expected to have broader potential. Investigations should be carried out to determine the value for other domains. Possibly the model needs optimisations for these applications.

The index-method focuses solely on the Independence Axiom. A method for indexing the information axiom could increase the understanding of product and process maturity in a broader sense.

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