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Enabling systems engineering in a new product development process via a tailored A3 architecture overview approach

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Abstract. This paper describes the development of a systems engineering (SE) approach to enable the application of SE and systems thinking in a new product development (NPD) process in an organization that is unfamiliar with the application of SE. The application of SE is enabled by using a tailored A3 architecture overview (A3AO) template. By using this template, a mechanism is presented to start the application of systems engineering in an organization that has limited experience with SE. By using A3AOs directly a way to capture and communicate the system architecture among stakeholders is provided. This approach is implemented and evaluated in a small-scale case-study.

Introduction

In industry systems engineering is applied more often and has many reported advantages. Projects where SE is applied perform better than projects that do not (Elm & Goldenson, 2012). Furthermore increasing the amount of SE-activities leads to better project performance in NPD-projects (Vanek et al., 2017). Also increasing the amount of SE-effort has a positive effect on cost and project quality (Honour). But how to start using SE in an organization that is unfamiliar with SE?

There are many available guides books and step-by-step guides about SE (Bonnema et al., 2016; Muller, 2011; NASA, 2017; SEBoK, 2017; Walden et al., 2015). Besides the SE-process is captured in a SE-standard; the most complete and revised SE-standard is the ISO/IEC/IEEE 15288 (Bougaa et al.). This standard state what should be done, but try not to say how to do it (National Defense Industrial Association, 2015) and a clear provision of how to start enable SE is often missing.

In a large-scale survey with leading technical companies (e.g. Miele, Audi, Siemens) concerns regarding application of SE were listed. 22 % of the respondents think they have *'insufficient provision of introduction methods'* and 21 % think they have *'insufficient expertise'* (Gausemeier et al., 2015). This shows the need to develop an approach to introduce SE to enable SE in smaller organizations that are unfamiliar with SE (i.e. provide an introduction method).

For an organization that is unfamiliar with SE, it is difficult to extract what SE is all about. Within Rademaker, the case company of this project the need for the application of SE was clear, but it was not directly clear how to start applying SE in their NPD-process.

Company background. Rademaker is founded in 1977 and is situated in Culemborg in the Netherlands. They deliver complete solutions in the food processing industry, with their key competence in the bakery industry. They develop advanced industrial dough processing installations and services for the worldwide market needs. The organization is developing and has the following challenges:

- Rademaker is growing; specialist engineering knowledge must be shared to more stakeholders.
- The technological complexity is increasing; machines and product lines are becoming more complex.
- Customers are becoming more demanding; customers demand a solution faster and have more specific demands.

Problem exploration. An approach to capture and communicate specialist engineering knowledge within the organization is needed. Besides an approach is needed that helps in understanding the increasing (system) complexity and should help in visualizing the impact of diverse customer demands to assist in development of new products.

Systems engineering is a discipline that can offer support in these areas. How to start using SE at a NPD-department is a difficult task and is not directly clear from literature. Literature provides a lot of knowledge, step-by-step guides, and some useful supporting tools are developed. But a clear provision on how to start applying SE is often missing. An easy and accessible instrument to enable SE, to create system overviews and to communicate the system architecture is needed.

Research goal. An approach needs to be developed such that SE can be applied within the NPD-process at Rademaker, more specifically a SE-approach that:

- Creates systems overview
- Captures the systems architecture
- Communicates the systems architecture
- Increases systems understanding among stakeholders

Based on interviews throughout the organization the following boundary conditions were found. A SE-approach was needed that is:

- Accessible
- Understandable; shall be used (and understood) by a wide range of stakeholders, cope with diversity, complexity and uncertainties in NPD-projects
- Easy to use; should be integrated in the current way of working, easy to manage, adjust and control

Research methodology. By using the following research structure shown in Figure 1, a tailored SE-approach will be developed. First the organization and the NPD-process are studied to determine where SE could add value. Hereafter SE-theory is studied, and it is determined which part of the SE-theory is applicable. By combining the results from phase I and II a tailored SE-approach will be presented. This approach is applied and evaluated in a case-study.

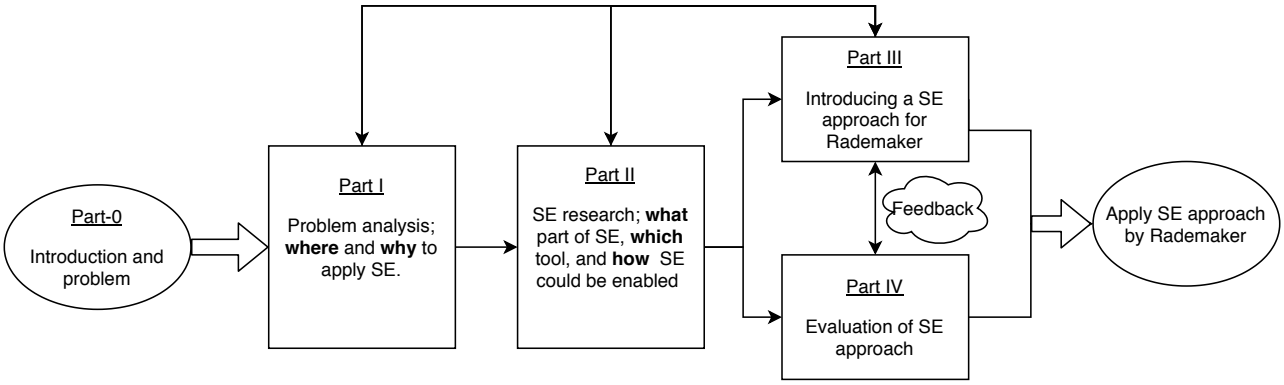

Figure 1. Research approach

Literature

Systems engineering. In a NPD-process a key aspect is to determine what needs to be developed. This needs to be translated to a system solution. Looking at ISO/IEC/IEEE 15288 this correlate to: the stakeholder needs & requirements definition process, system requirements definition process and architecture definition process. In these processes it is defined what the customer wants, what the system must do to fulfill the customer needs and how the system should be developed such that it fulfills the system requirements (the system architecture) (Walden et al., 2015).

Systems thinking. Systems thinking can help to solve problems with many stakeholders, reoccurring problems and problems were solutions are not directly obvious (Aronson, 1996). Systems thinking can be stated as: 'Seeing the whole beyond the parts' and 'seeing the parts in the context of the whole' (Shaked & Schechter, 2017). Systems thinking can offer support in multiple areas (Frank, 2012). Key systems thinking skills are summarized in Figure 2.

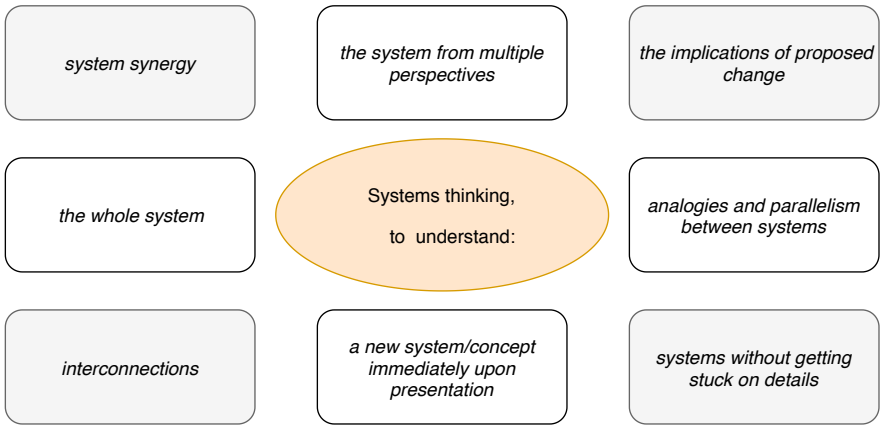

Figure 2. Systems thinking skills, adapted from (Frank, 2012)

In a NPD-process systems thinking can help to:

- See the whole system; what is the to be developed system all about?
- Understanding the system without getting stuck on the details; first understanding what is needed for the customer before diving into engineering details too soon
- Implications of proposed change; understand the impact of changing customer demands
- Analogies and parallelism between systems; are there systems that share the same aspects (i.e. can knowledge be reused).

A3 architecture overviews. In an A3 architecture overview (A3AO) the system architecture is captured on a two-sided A3-document. One side of the A3AO is used for models and visual aspects. The other side is used to elaborate on the models with text. This division ensures that the overview is easy to read. Key strengths of this tool are its brevity, it provides a shared model and it consolidates (architecture) knowledge in a compact and visual way. A3AO are initially developed to capture an existing (complex) architecture to support the evolution of existing systems (Borches Juzgado, 2010).

Earlier research has shown that A3AOs are considered as a good tool to communicate and capture the system architecture (Løndal & Flak, 2018). By using the A3AO most import aspects of the system (architecture) can easily be shared and consumed among stakeholders.

In a NPD-process there is not yet a clear existing system architecture to capture (still under design). To handle this aspect a way has to be found to make A3AOs applicable in a NPD-process where directly the core SE-processes can be applied and systems thinking can be initiated.

Concept elaboration

The A3 architecture overview approach is tailored such that it can be applied in the NPD-process. In this tailored approach emphasis is on the SE-activities to support the development of new products. The SE-process as defined in ISO/IEC/IEEE 15288 is integrated into this approach via a step-by-step guide. By using this step-by-step guide to build an A3AO the stakeholder needs & requirements definition process (step 1), the system requirements definition process (step 2 and 3) and the architecture definition process (step 4, 5 and 6) are executed and the results are captured In an A3AO.

In Figure 3 the relation between the SE-process and the NPD-process is shown. Emphasis in on the product definition and conceptualisation phase. In the product definition phase, the customer wish is formulated (user needs) and translated to the system requirements. In the conceptualization phase the system functions are allocated to subsystems (function allocation).

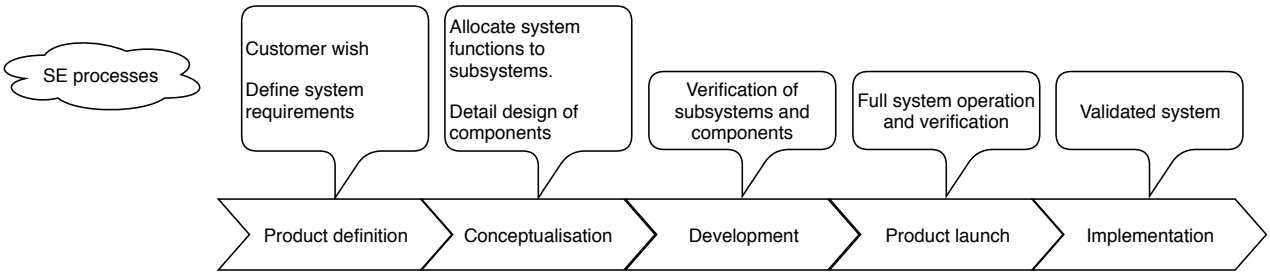

Figure 3. The NPD-process and SE-activities

By connecting the SE-processes and the NPD-process to the A3 architecture overview approach (Figure 4) a medium is given to execute the SE-process. The relation between each SE-activity, step and place in the A3AO is marked by colors. This tailored approach has two implications, it provides a mechanism to start applying SE and directly offers a medium to capture and communicate this knowledge.

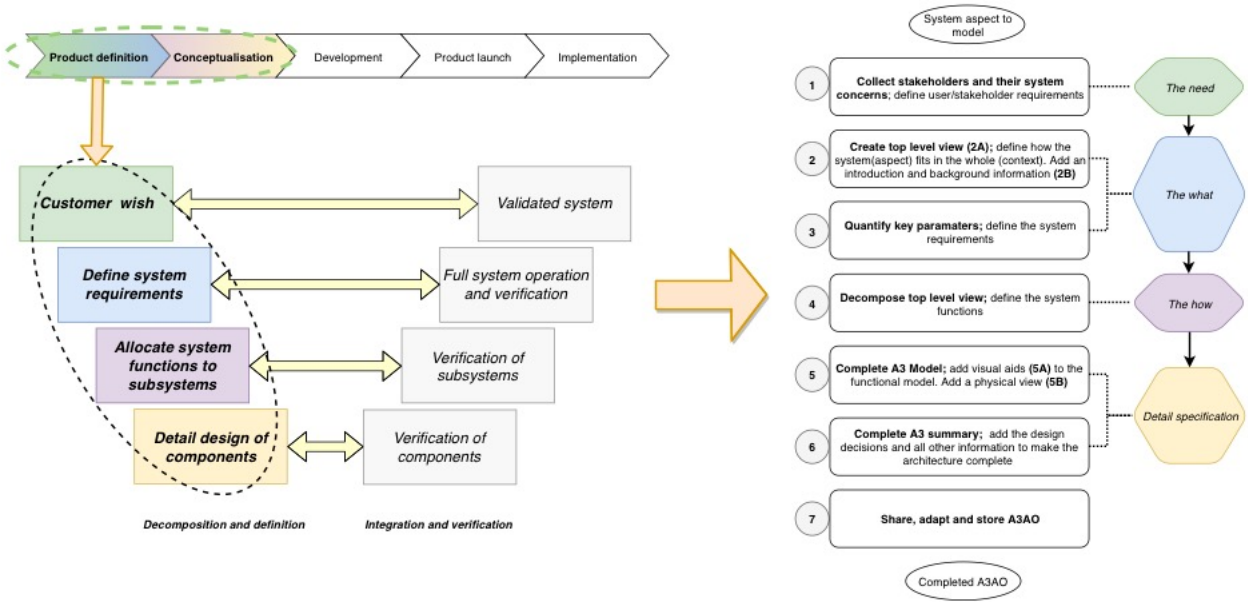

Figure 4. The NPD-process, the SE-process and A3AO steps

By following the steps as shown in Figure 4 and Figure 5 an A3AO is build. By building an A3AO directly the ISO/IEC/IEEE 15288 SE-process is executed, as shown in Figure 5. The results are captured on a A3AO. This ensures that knowledge can easily be shared and because of its brevity it can easily be 'consumed' by the reader.

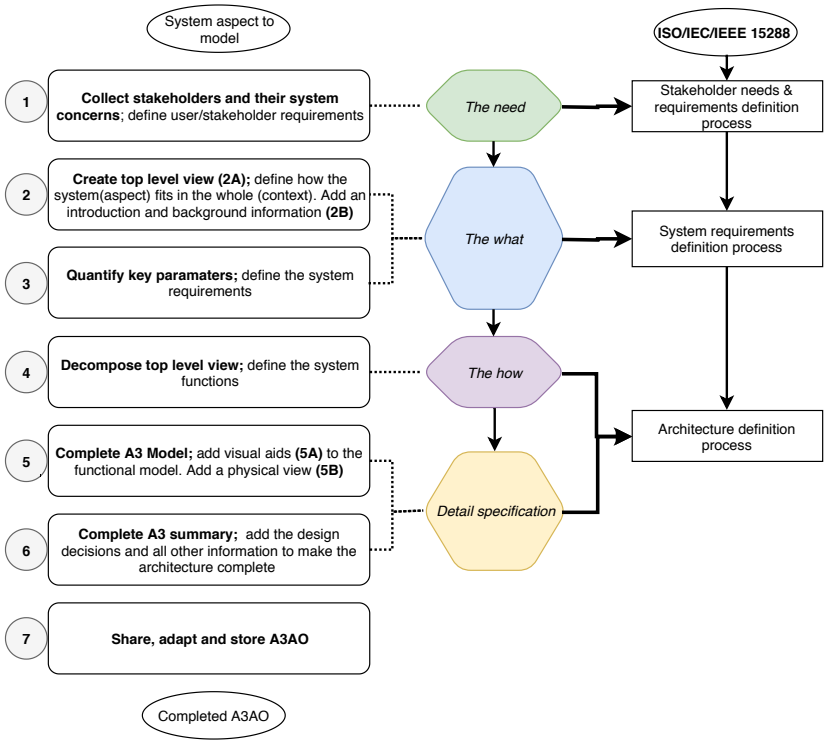

Figure 5. The relation between A3AO steps and ISO/IEC/IEEE 15288

The results of these steps are captured on a two-sided A3 document (Figure 6 and Figure 7), the A3-model (steps 3, 4, 5A and 5B) and the A3-summary page (steps 1, 2A, 2B and 6).

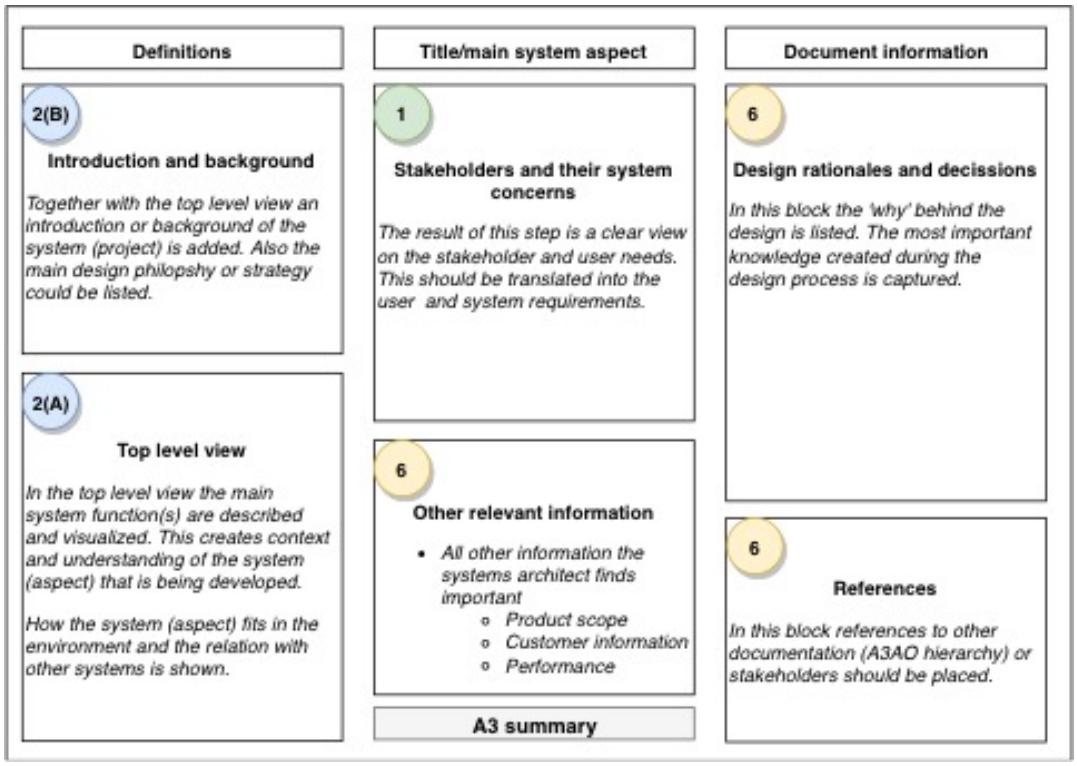

Figure 6. The tailored A3AO summary page structure

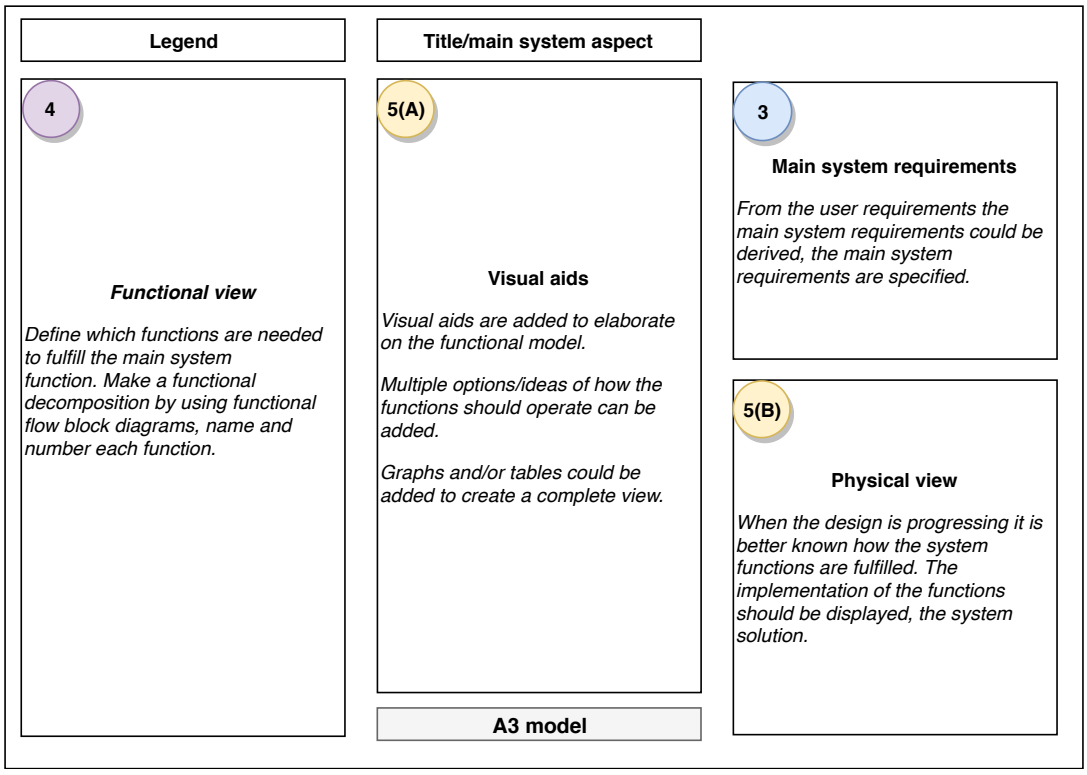

Figure 7. The tailored A3AO model page structure

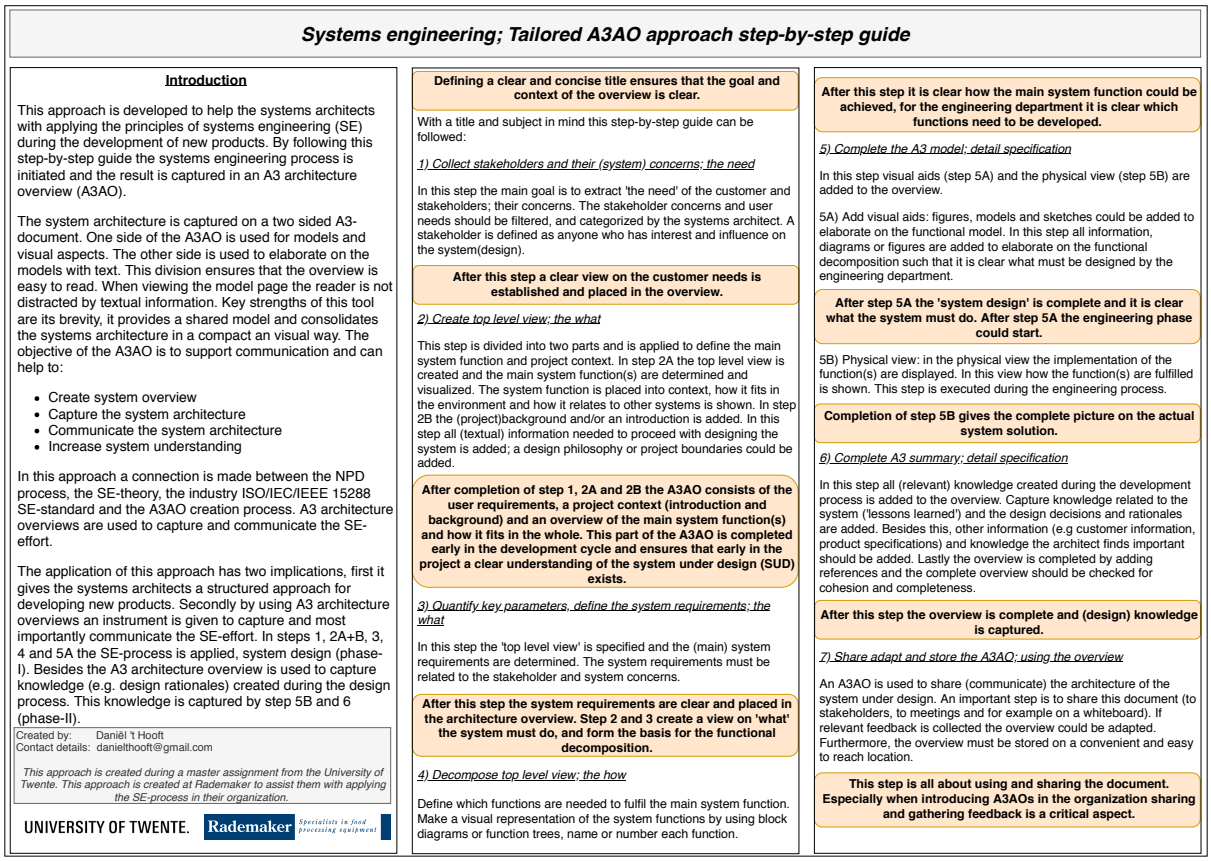

Figure 8. Tailored A3AO approach manual (see appendix)

The Tailored A3AO approach itself is compressed such that all the information fits on a double sided A3-paper. On the front side of the A3, the structure of the overview and the correlation with the NPD-process and SE-process is shown (Figure 3, Figure 4, Figure 5 Figure 6 and Figure 7). On the back side of the A3 textual information is presented and each step is explained (Figure 8). The complete tailored A3AO approach is added as an appendix and can be found at http://a3ao.eu/ (under A3AO for new product development). By presenting and compressing the approach on such an overview it is ensured that it is easy to share. By reading this A3AO manual it is possible to 'build' an A3AO and directly start applying SE.

Application of A3AOs. This approach is developed to help to start the enabling of SE in organizations that have limited experience with SE. It is not possible to capture the complete SE-process on an A3AO nor is it possible to capture all SE-knowledge on a double sided A3 paper. A3AOs are used as a tool to share and communicate knowledge during the development process. During meetings an A3AO can easily be understood. Furthermore, integrating the (simplified) SE-process in an A3AO provides a clear guidance how to apply the SE-process during the development process. In this approach emphasis is on the 'system decomposition' (i.e. left side of the v-model). This approach is meant for organizations that are not familiar with SE were there aren't any comprehensive SE-processes already at use. (i.e. model based systems engineering (MBSE)).

Implementation

For the application of a new approach in an organization a vision, skills, incentives, recourses and an action plan are needed (Casali, 2015). In three Systems engineering sessions (SES) (Figure 9, the action plan)) the theory and approach (the incentive) is introduced and implemented. These sessions ensure that there was enough knowledge about SE and this approach before applying it.

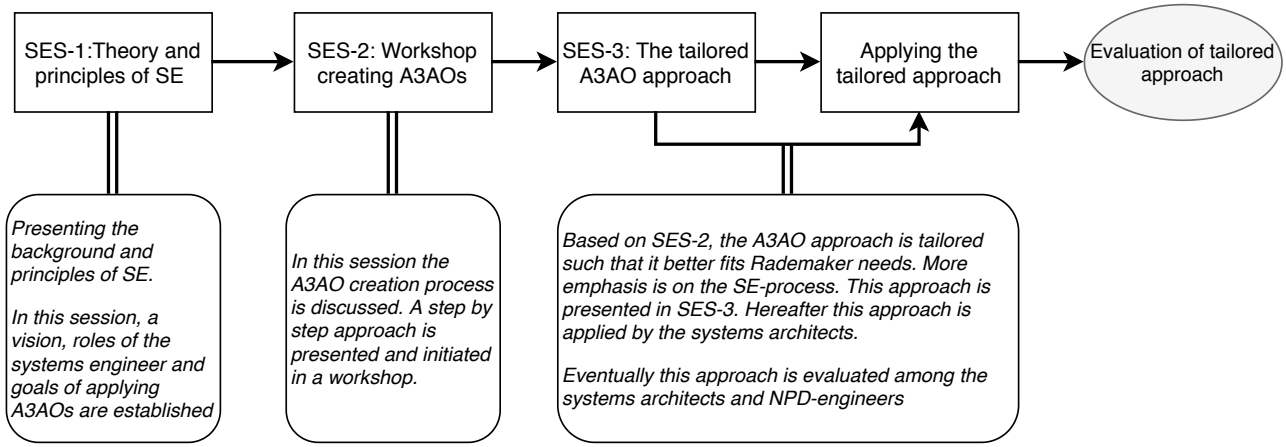

Figure 9. Implementation process

Evaluation

The approach is evaluated on two levels in the organization. First the usefulness of this approach for the creators (i.e. Rademakers systems architects) is established. This evaluation is done with 2 system architects. Secondly the approach and the created A3AOs are presented to a group of NPD-engineers. In this evaluation the value of the A3AO (as a document) is established and it is evaluated if the approach itself is applicable by other engineers in the organization. In both evaluations results are obtained via a 5-point scale survey and feedback is gathered via open questions. The evaluation process is shown in Figure 10.

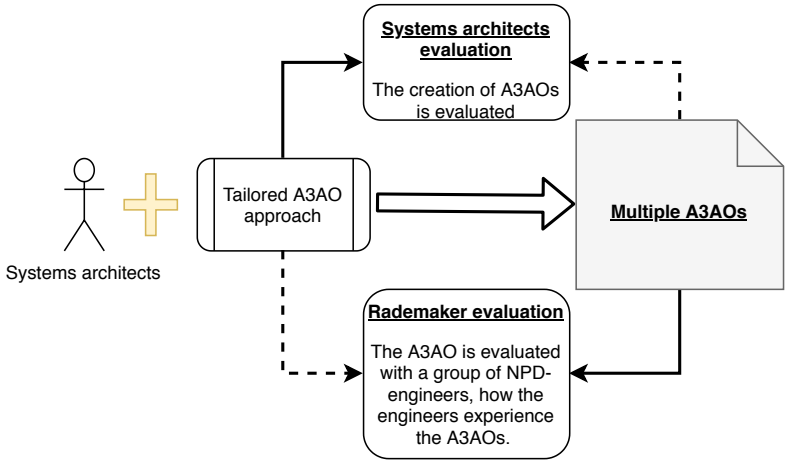

Figure 10. Evaluation process

Systems architects evaluation. The results among Rademakers systems architects are shown in Figure 11 and Figure 12. Results are obtained by 2 systems architects.

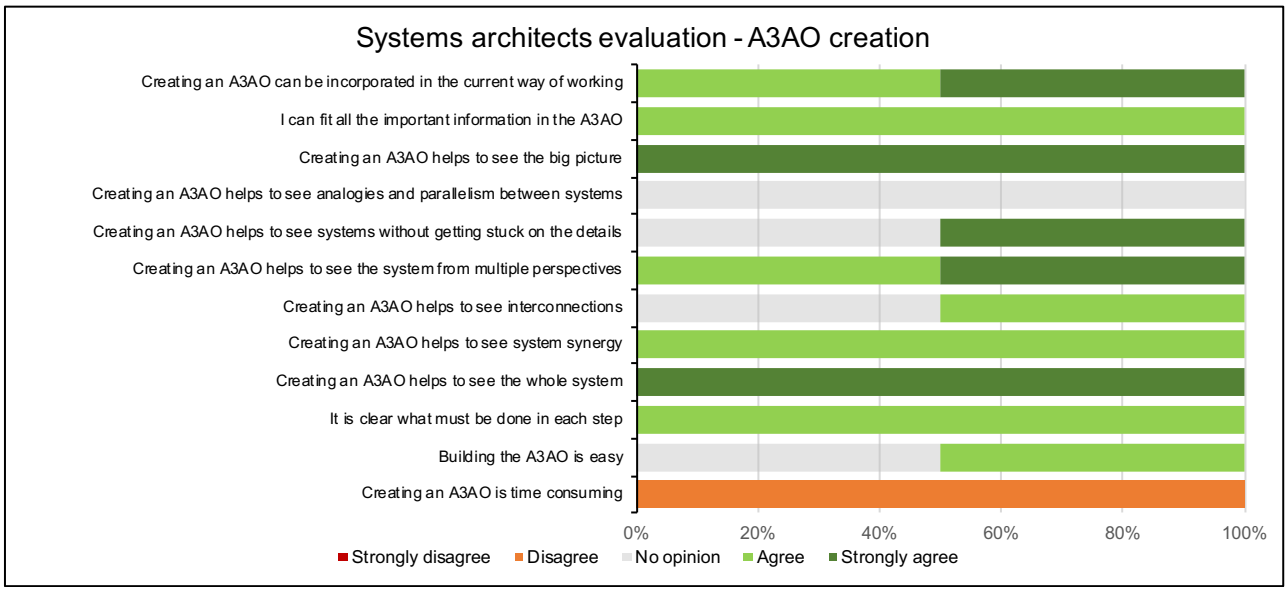

Figure 11. Systems architects evaluation, A3AO approach

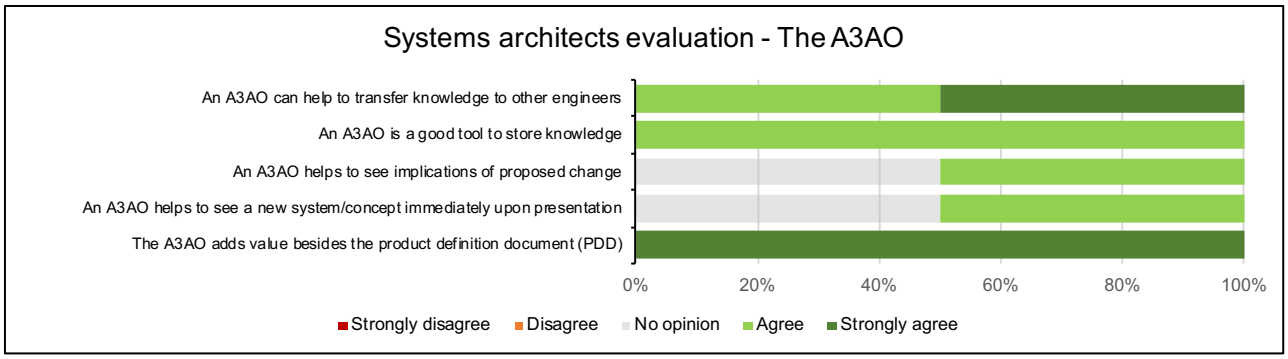

Figure 12. Systems architects evaluation, A3AO

Besides these results, valuable oral feedback was given. The systems architects mentioned that via this step-by-step approach systems thinking is introduced (seeing the big picture). Because of the sequence in the creation process more emphasis is put on the customer whish and demand. Besides it was reckoned that within an A3AO it is easy to highlight what is really important and A3AO offers a mechanism to capture knowledge.

Rademakers evaluation. The results of the evaluation among the NPD-engineers is shown in Figure 13 and Figure 14. Result are obtained from 7 NPD-engineers. The NPD-engineers rate the usability of an A3AO by an 8.1 (n=7).

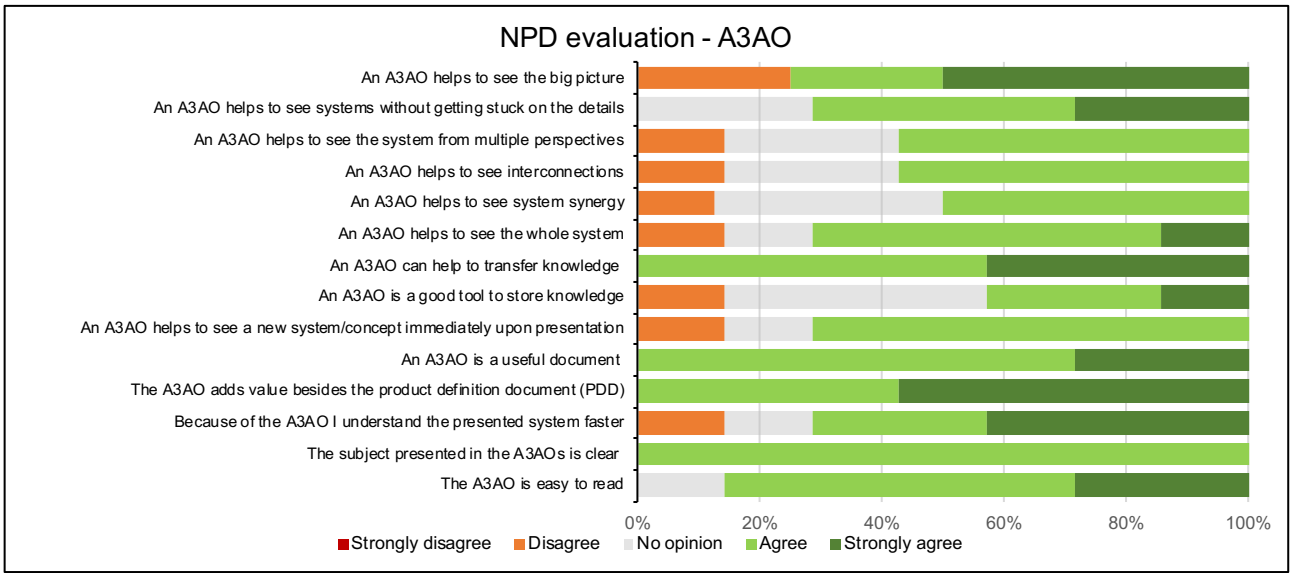

Figure 13. NPD-engineers evaluation A3AO

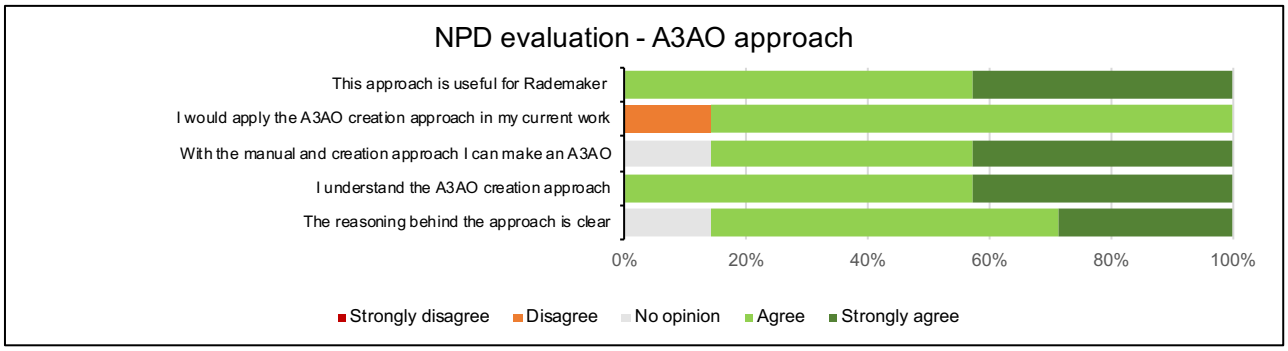

Figure 14 NPD-engineers evaluation A3AO approach

Discussion

It has to be noted that the results are obtained from a limited group, but initial results show that this approach is received positively at Rademaker. The creation of A3AOs is evaluated with two systems architects at Rademaker (n=2). The created A3AOs and approach is presented to a group of seven NPD-engineers (n=7). Because of this, results are not statistically significant.

The approach was applied on projects that were already almost finished and should be seen more as showcase. In this evaluation the approach is not yet applied on a new NPD-project. Therefore, this evaluation only shows the potential usability of this approach.

This paper is written to show that this tailored A3AO approach helps to enable SE in organizations were there aren't any comprehensive SE-processes already at use. The strength of this approach is its brevity and the ease in which it could be applied and understood. An A3AO is a mechanism to communicate the SE-activities among stakeholders. A connection with model-based approaches (i.e. MBSE) should be made, in which A3AOs could be used as a communication tool for MBSE. A recommendation is to connect the strong bases for MBSE with the communicable form of A3AOs.

Follow-up results. After one year of use at Rademaker already over 40 A3AOs were created with varying complexity and scope. At the moment of writing this approach is fully incorporated in the NPD-process at Rademaker. A3AOs are received positively by a wide group of stakeholders and are also applied by other engineers within the organization. Using this approach encourages systems thinking on a high level, without diving into engineering details too soon. To conclude it is mentioned that this approach is seen as the missing link between the condensed and well documented SE-theory and practice. This approach helped to start the application of SE in the NPD-process.

Conclusions

A way to apply (the principles of) SE in the NPD-process at Rademaker in an accessible, easy to use and understandable manner was needed. An approach is presented that makes it possible to facilitate systems engineering and to initiate systems thinking in the NPD-process. Both systems architects agree that this approach can be incorporated in their current way of working and both state that creating an A3AO is not time consuming. By presenting the tailored A3AO approach on an A3- document accessibility of this approach is achieved. The evaluation among the NPD-engineers shows that this approach is understandable and accessible (6 out of 7 engineers would apply this approach in their current way of working). By the NPD-engineers the usability of an A3AO is rated by an 8.1 (n=7).

SE was desired; to create system overview, to capture and communicate the system architecture and to increase system understanding. Both systems architects strongly agree that the creation of an A3AO helps to see the big picture and help to see the whole system. All NPD-engineers and both systems architects agree that an A3AO helps to transfer knowledge. All NPD-engineers agree that the subject presented in the A3AOs is clear thus can assist in system understanding.

By combining the SE-process with the NPD-process and merging it within a tailored A3AO approach a template is given to start applying SE. By following the step by step guide and by ‘building’ an A3AO the main SE-process (Stakeholder needs and requirements definition, System requirements definition and Architecture definition process) are executed (i.e. system decomposition). Via this approach the SE process is made explicit and the result is captured in an A3 architecture overview (A3AO). By using A3AOs a mechanism is presented to apply, capture and communicate the SE-process among stakeholders.

In this approach A3AOs have found a new purpose. With this template, A3AOs now can be used in a new product development process. To develop completely new systems (instead of capturing an existing system architecture/knowledge). Earlier initiatives of A3AOs has found clear benefits of A3AOs but it was rarely used today (Løndal & Flak, 2018). By providing this A3AO template and approach not only the approach is applied and evaluated in a short-term research session, after one year the approach is fully embraced and incorporated in the current way of working. A3AOs are received positively by a wide group of stakeholders and are also applied by other engineers within the organization.

Future work

This approach is presented and evaluated to a small group of engineers. In this evaluation ‘opinions’ of the participants are captured. For conclusive results it is necessary to get data from a larger group of engineers inside Rademaker. In addition, most research about this topic is ‘short-term’ research. It can be a very valuable addition to do a quantitative research on this topic in a long-term case-study. This means gathering some ‘hard’ data of the application of this approach; to quantify the real benefits of such an approach this can be done by doing a long-term case study in a larger scale application.

In doing so it is directly advised to try a comparison study with a control group. This is a challenge because most engineering projects are never the same, but it will definitely be valuable to gather some measurable advantages of using such an approach.

Lastly an interesting research topic is how A3AOs could be used in collaboration with MBSE. Is it possible to use A3AOs as a communication tool for MBSE approaches?

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Biography

Daniel ‘t Hooft has a bachelor and master’s degree mechanical engineering from the university of Twente. He did his graduation assignment at Rademaker where an approach is developed how to enable systems engineering in a new product development process. Currently working as a consultant in the railway industry.

David van Omme works as a systems architect at Rademaker.

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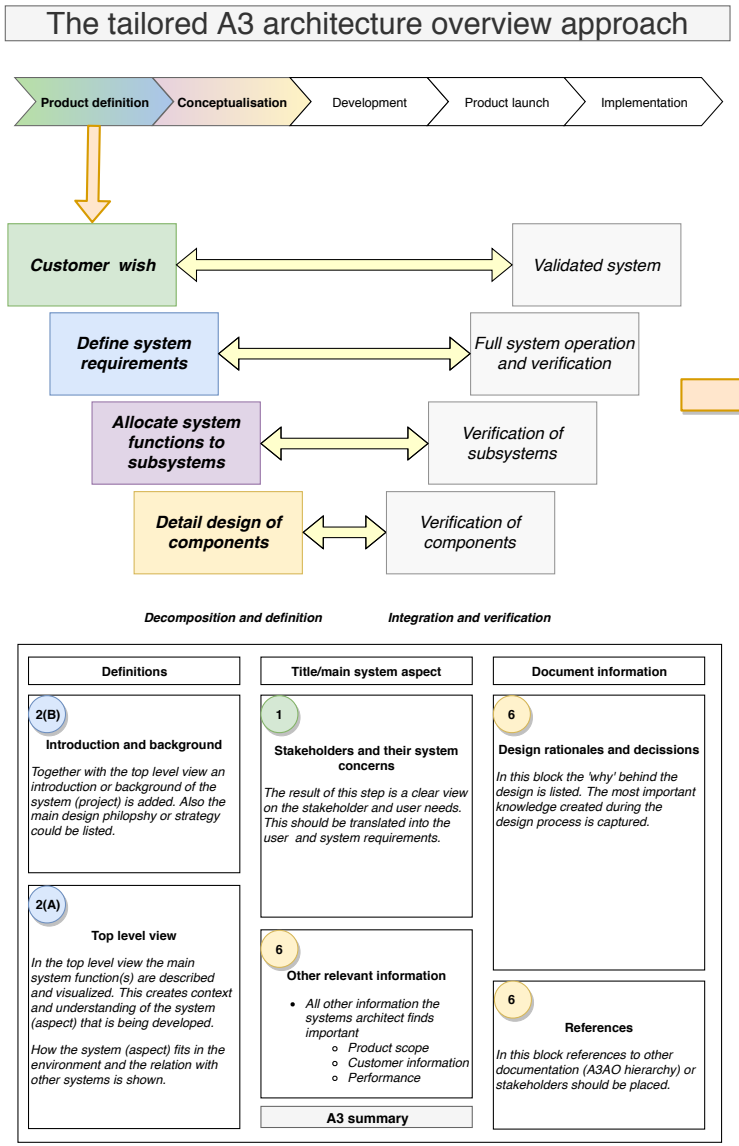
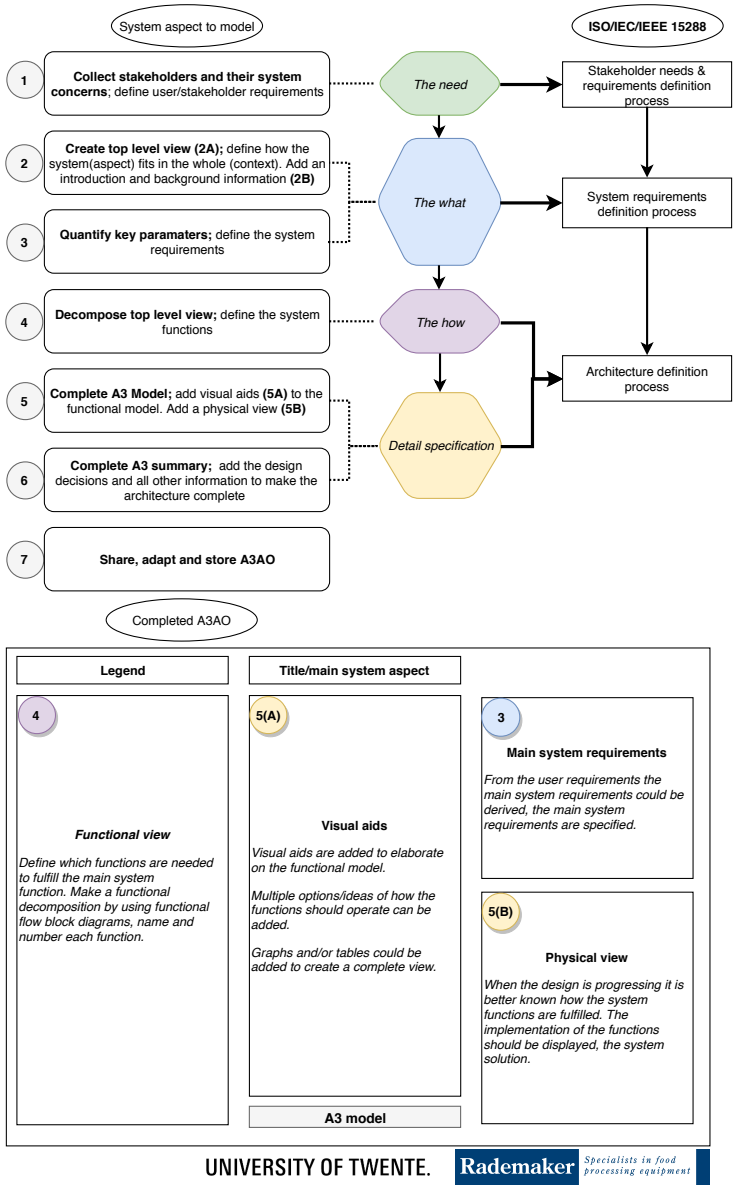
G. Maarten Bonnema is an associate professor in systems engineering and multidisciplinary design at the Department of Design, Production and Management of the Faculty of Engineering Technology at the University of Twente. He has worked as a Systems Engineer at ASML. His research aims at supporting system designers, conceptual design and mechatronic design by improving multidisciplinary communication, and systems thinking. An overview of publications can be found at http://www.tinyurl.com/MaBoPubs. Two main application areas are high-tech systems and electric mobility. He has a broad teaching expertise spanning design in general, industrial design, and systems engineering.

Appendix





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Systems engineering; Tailored A3AO approach step-by-step guide

Introduction

This approach is developed to help the systems architects with applying the principles of systems engineering (SE) during the development of new products. By following this step-by-step guide the systems engineering process is initiated and the result is captured in an A3 architecture overview (A3AO).

The system architecture is captured on a two sided A3-document. One side of the A3AO is used for models and visual aspects. The other side is used to elaborate on the models with text. This division ensures that the overview is easy to read. When viewing the model page the reader is not distracted by textual information. Key strengths of this tool are its brevity, it provides a shared model and consolidates the systems architecture in a compact an visual way. The objective of the A3AO is to support communication and can help to:

- Create system overview
- Capture the system architecture
- Communicate the system architecture
- Increase system understanding

In this approach a connection is made between the NPD process, the SE-theory, the industry ISO/IEC/IEEE 15288 SE-standard and the A3AO creation process. A3 architecture overviews are used to capture and communicate the SE-effort.

The application of this approach has two implications, first it gives the systems architects a structured approach for developing new products. Secondly by using A3 architecture overviews an instrument is given to capture and most importantly communicate the SE-effort. In steps 1, 2A+B, 3, 4 and 5A the SE-process is applied, system design (phase-I). Besides the A3 architecture overview is used to capture knowledge (e.g. design rationales) created during the design process. This knowledge is captured by step 5B and 6 (phase-II).

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This approach is created during a master assignment from the University of Twente. This approach is created at Rademaker to assist them with applying the SE-process in their organization.

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Defining a clear and concise title ensures that the goal and context of the overview is clear.

With a title and subject in mind this step-by-step guide can be followed:

1) Collect stakeholders and their (system) concerns; the need

In this step the main goal is to extract 'the need' of the customer and stakeholders; their concerns. The stakeholder concerns and user needs should be filtered, and categorized by the systems architect. A stakeholder is defined as anyone who has interest and influence on the system(design).

After this step a clear view on the customer needs is established and placed in the overview.

2) Create top level view; the what

This step is divided into two parts and is applied to define the main system function and project context. In step 2A the top level view is created and the main system function(s) are determined and visualized. The system function is placed into context, how it fits in the environment and how it relates to other systems is shown. In step 2B the (project)background and/or an introduction is added. In this step all (textual) information needed to proceed with designing the system is added; a design philosophy or project boundaries could be added.

After completion of step 1, 2A and 2B the A3AO consists of the user requirements, a project context (introduction and background) and an overview of the main system function(s) and how it fits in the whole. This part of the A3AO is completed early in the development cycle and ensures that early in the project a clear understanding of the system under design (SUD) exists.

3) Quantify key parameters, define the system requirements; the what

In this step the 'top level view' is specified and the (main) system requirements are determined. The system requirements must be related to the stakeholder and system concerns.

After this step the system requirements are clear and placed in the architecture overview. Step 2 and 3 create a view on 'what' the system must do, and form the basis for the functional decomposition.

4) Decompose top level view; the how

Define which functions are needed to fulfil the main system function. Make a visual representation of the system functions by using block diagrams or function trees, name or number each function.

After this step it is clear how the main system function could be achieved, for the engineering department it is clear which functions need to be developed.

5) Complete the A3 model; detail specification

In this step visual aids (step 5A) and the physical view (step 5B) are added to the overview.

5A) Add visual aids: figures, models and sketches could be added to elaborate on the functional model. In this step all information, diagrams or figures are added to elaborate on the functional decomposition such that it is clear what must be designed by the engineering department.

After step 5A the 'system design' is complete and it is clear what the system must do. After step 5A the engineering phase could start.

5B) Physical view: in the physical view the implementation of the function(s) are displayed. In this view how the function(s) are fulfilled is shown. This step is executed during the engineering process.

Completion of step 5B gives the complete picture on the actual system solution.

6) Complete A3 summary; detail specification

In this step all (relevant) knowledge created during the development process is added to the overview. Capture knowledge related to the system ('lessons learned') and the design decisions and rationales are added. Besides this, other information (e.g customer information, product specifications) and knowledge the architect finds important should be added. Lastly the overview is completed by adding references and the complete overview should be checked for cohesion and completeness.

After this step the overview is complete and (design) knowledge is captured.

7) Share adapt and store the A3AO; using the overview

An A3AO is used to share (communicate) the architecture of the system under design. An important step is to share this document (to stakeholders, to meetings and for example on a whiteboard). If relevant feedback is collected the overview could be adapted. Furthermore, the overview must be stored on a convenient and easy to reach location.

This step is all about using and sharing the document. Especially when introducing A3AOs in the organization sharing and gathering feedback is a critical aspect.