Model Based System Engineering guidance framework for the technological installation in the infrastructure sector

A qualitative study investigating and designing a guidance framework and process for MBSE in the TII sector

R.T. (Robin) Winters, 2019
Master student Complex Systems Engineering and Management (CoSEM)
Faculty of Technology, Policy and Management – TU Delft

Abstract - Today's increasing complexity, rising interconnectivity and larger systems in engineering require new approaches and methods for effective engineering. This is also the case for the technological installation in infrastructure sector (TII), which designs technical systems for infrastructural civil structures. To assist in engineering, Model Based System Engineering (MBSE) can be implemented that provides more control and linkage by means of modelling. The implementation process for MBSE is limited described in literature, especially for the TII sector. Desk research helped to understand and characterize the challenges of the TII sector. By means of in-depth interviews with Siemens Mobility engineers next, requirements were developed. Based on those requirements a framework for implementation of MBSE was constructed that consists of eight building blocks. An implementation process was constructed that puts the framework blocks in order and adds more information for implementing MBSE. The main component, the actual modelling, is split up into technical and process modelling. The technical modelling is fed by the choices and interactions of the process modelling. In the implementation process described which framework blocks are important at what moment, as well as update characteristics of the eventually MBSE environment. In the end, the MBSE methodology and the designed process with framework blocks seem promising for maintaining control of future engineering projects. It provides structure to for setting up the new engineering methodology for the TII in special.

Keywords – Model Based System Engineering, MBSE, infrastructure, framework, multi-disciplinary, complex, modelling, implementation process

1. Introduction

In the last decades, the transformation from electromechanical systems towards software intensive systems has changed the way of engineering in multiple sectors. With the future trend towards cyber-physical systems, complexity is rising. In the Technological Installations in Infrastructure (TII) sector, this change triggers engineering companies to think ahead and come up with new engineering methodologies to facilitate the changing environment. The TII sector engineers projects like bridge, tunnels, water locks and weirs.

Not only the systems change, also the deferred maintenance of last decades, especially in the Netherlands, cause a large amount of renovation projects to be put onto the market coming years [1]. The renovation does not only relate to the civil engineering branch, but also the technical systems that are the brain, eyes and ears of the infrastructure. Systems like CCTV, automated incident detection, control and ventilation systems that are more technology intensive. More sensors, detectors, actuators and software make engineering for TII companies less straightforward. The current System Engineering (SE) method in the sector does work well with the civil engineering branch, but the intensive software systems require more guidance. From a governmental perspective, their TII attention for technical systems is increasing. Digitalization, information provision and industrial automatization (IA) show the rapid changing environment on one side, with stricter requirements on RAMS (Reliability, Availability, Maintainability, Safety), cyber security and circularity on the other [2]. The enlarging, increased connected and entangled systems require new engineering techniques to be able to handle the increasing amount of information for successful project development.

Current literature describes multiple methods that focuses on integration of systems and collaboration between design teams and disciplines. One of these innovative methods is Model Based System Engineering (MBSE), originated at the complex product development. The MBSE methodology elevates different disciplines and systems in the engineering process to a central meta model that has a governing role in operation, specification, design, integration and validation of the systems [3]. Changes can be handled to all related components more straightforward, to support engineering in a higher extent [4]. Research has been conducted in this direction, but it remains unclear how the method holds in TII projects. As Friendenthal described as well, current literature does not describe the total support of modelling, but mainly relates to specific types of analysis or aspects of systems [5]. In relation to this, the main research question is:

What is a useful framework to support the development of MBSE, in order to structure and align the engineering processes and artifacts in complex multi-disciplinary infrastructural engineering projects?

The purpose of this research was first to identify the TII sector and understand the challenges of the sector for coming decades. Next a customized framework for implementing MBSE in the sector was constructed together with an implementation strategy. In section 2 the literature around complex design projects is discussed, followed by the research methods in section 3. In section 4 the results of the multiple components are given and the discussion in section 5 elaborates the results. In section 6 the paper is concluded and section 7 provides recommendation for further research.

2. Literature review

In the field of complex and/or integrated designing, multiple methods exist to support or guide engineering companies. Complex systems are seen as environments wherein a change of a component also results in (unexpected) changes in other components and systems [6]. The single change leads to a range of changes, that might be difficult to predict and process with various impacts [7]. To be able to design the system as a whole, current SE methodology divides the system into subsystems, with the aim of integration later on. Due to this sub division it might not lead to the optimal solution in the end [8]. When the amount of interfaces with the new and larger interconnected systems rises beyond control, what methods, processes and tools support these new principles? [9].

Current widely used method, as described above, is System Engineering (SE). Although widely used in the sector, the usage seems to be suited for civil engineering and less for the software/hardware systems developed by the TII side of a project. As Fosse describes, current SE boundaries are [10]:

- Complexity is growing faster than the ability to manage it.

- System design emerges from pieces in SE, instead of overall architecture
- Knowledge is lost in- and between projects.

The SE methodology is mostly used to structure the engineering process in main lines, but the actual detailed engineering is not described and guided by the method.

A method that is used for describing the dependencies (interfaces) more extensively is the design structure matrix (DSM). The matrix describes the relations of all components to provide overview and indication of the interfaces. The matrix is mainly based on interfaces, and therefore also the tool looks promising for a structuring tool in engineering [11][12][13]. DSM is widely used in product development, where physical products are engineered (like coffee machines). To solve larger systems, in this case up to 40 subsystems, the method might be too limited [14]. Also the dynamic side, on how time and planning can be implemented and the actual descriptions of the interfaces are missing, and therefore giving limited answers to the complex design challenges in this sector [11][15].

To rely on a central project management environment where information is shared, Virtual Design Teams (VDT) can enhance shared information and coordination [16]. The virtual environment establishes a common ground and negotiation mechanism in order to manage the integration of design perspectives and designs [17]. The central approach, where information links are short and based on a platform and interaction is initiated instead of documents are beneficial here. Although the central approach is a step in the right direction, it does not support the actual engineering.

Another more used methodology focused on engineering is concurrent design. The method, also with roots in the product development (e.g. space shuttles), has as main elements the architecture phase followed by parallel engineering. In the architecture phase, the suppliers and customers are involved, to define the innovative tasks (around 20% of the tasks). The first phase, will have a high impact since most important choices are made, on which the engineering in parallel phase will be based. In this later parallel phase, consisting of around 80% of the tasks, it is mainly routine execution tasks [18]. With this setup, the architecture phase has high priority and defines the success of the later phases. A skilled team is preferred to make the right choices and involvement of all actors is important. The method becomes a challenge when not all required information is available, and when is worked on multiple projects with large groups. Also the choices made at the start might change during engineering, which results in a wider spread of changes.

The final specialized engineering method discussed is Model based system engineering (MBSE). As described earlier, the methodology is a evolution of SE and also relies on the structure of SE. The main difference is that now (meta) models are constructed in which all systems are connected. The changes can be handled throughout the other systems more conveniently [4]. With the modelling technique, complex technical systems can be modelled, but also connected to other systems. In that way, control may be maintained with enlarging systems and in which software is central [19]. The output of those models can be used in different disciplines, depending on what specifically is required. The usage of MBSE is emerging in the product development sectors, and still new in the TII sector. The TII sector is different compared to the product development sector, and therefore also a slightly customized approach is required to be able to apply MBSE correctly.

The question remains on how can a customized approach for MBSE be designed, to achieve the right guidance for a high quality environment. This is in line with the literature gap, in which little research is conducted to setup the MBSE, especially for the TII sector.

Since development of MBSE might be costly initially, doing the right thing from the start becomes important [4]. In the following chapters the TII sector is researched and a framework design is proposed to construct MBSE. The research is finalized by a implementation process for MBSE with the use of the framework blocks.

3. Methods

To be able to understand the TII sector and to define what is required in future engineering environments, the research is split up into two main components.

First, the sector is analyzed from two perspectives. On one hand the characteristics and complexity levels are researched, followed by research on future developments of the TII sector. For this part of the research, desk research and exploratory interviews are used to gather data. Desk study on current and future developments in the sector, but also interviews with engineers to define what characterizes the TII projects and to what extend complexity is a factor.

The second part of the research contains in-depth interviews with lead engineers. This part dives deeper into the goals and needs of engineers to fully understand what is required and needed to ease engineering and remain future proof. The outcome of the interviews is used to define needs on which the framework will be constructed.

For the interviews a semi-structured approach was chosen, in which a set of main topics were the redline throughout the interview. This structure allowed to also freely speak about other subjects and dive deeper into certain special topics. The main topics that were discussed during the interview are:

- What characterizes the TII sector
- Existing engineering processes
- Typical issues and challenges during the engineering process
- Setup and usage of interface information
- Organizational setup
- MBSE methodology and other future developments

To construct a wide view of engineering disciplines, a lead engineer of the main five disciplines was interviewed. After the interviews, the data (of the conversations) is processed and divided into six main challenge levels (organization, technical, process, individual, environmental and digitalization). The levels describe per topic what challenge the engineers are facing. In the end these will be transformed to needs for reference during framework development.

The final step in the process is to implement a feedback iteration. After the framework and implementation process concept are designed, a feedback session was held to accommodate this. It delivered valuable remarks straight from the field, which were implemented into the framework afterwards.

4. Results

The results of the research can be divided into two main components. The first part relates to understanding MBSE and the TII sector. It describes how MBSE might be beneficial for the sector and give insight in the TII sector from different complexity levels. In the second part, the focus is on the development and design of the MBSE framework and process.

Model Based System Engineering
In MBSE, the individual models (depending on the systems and tools) are connected by a meta-model. This meta model stands between subsystems and provides guidance and clearance in the interfaces. To arrive at such a meta model and the individuals models, guidance is required to transform the engineering methodology. The research aim was to deliver a framework and process to structure the development of MBSE for TII sector

companies. In the following section the TII sector is further researched to define the sector.

TII sector

To understand the sector on how it evolves and changes, exploratory interviews were conducted and desk research was used to define the sector. First common challenges in engineering are described, followed by more specific challenges and complexity topics. The complexity topics are divided into three main parts: technical, organizational and institutional [26].

Common design challenges

To described more specific challenges of TII projects, exploratory interviews with Siemens engineers are held to understand project specific challenges they have faced. These challenges will then be used to further develop the in-depth interview content for the framework development. The general challenges can be described by the following points:

Organizational division

Division is based on subsystems with responsible lead engineers. Next to this division, also discipline leads are appointed that accommodate the coordination. The division works well, but actual engineering requires more steering for direct consequences and indications of changes.

Processes

Especially in large projects, mostly simple processes are repeated multiple times (100-1000). The administrative work does ranges from simple face-to-face communication and to excel files, in which mistakes could easily be made.

Information delays

Although a planning will be made, certain engineers might deliver information too late or forgets to deliver. This can lead to deadlocks in which time and costs might be lost.

Interfaces

Defining interfaces and understanding them correctly is an important step at the start of projects. Forgetting interfaces or misinterpreting could results in later rework and delays in engineering.

Changes

An important aspect of engineering is dealing and managing the changes. When a component is changed, others might have to perform changes as well. Discussing the change and impacts is now a time and costly process.

Process description

Engineering is partially described by the client (SE process), but mainly on the greater deliverables. Every project does have a unique approach to tackle the project and moving from project to project, the work is always slightly different. This can cause problems in reusing and therefore innovation become more difficult.

Work packages

Next to the processes at projects in the section above, the work packages therefore also cannot be easily set. If every project is different, copy/paste becomes more difficult and responsibility levels drop with enlarging wait-and-see tensions as a consequence. Also exploratory interviews with Siemens engineers showed more challenges:

- Manual labor in large projects sensitive for mistakes
- Amount of information interfaces larger than normal (Stockholm By-pass)
- Innovative project (3B/Wantij) are a challenge to engineers (other mindset)
- Memory of engineers is not always sufficient for conducting activities
- Integration of all parties in project needed for optimal project engineering
- Innovation comes after standardizing. Define the outside interface for inside innovation.

Technical complexity

An important point is the technical complexity of subsystems. From multiple conversations it came forward that the pure technical complexity is not the main issue at TII projects. The main challenge engineers do experience is the amount and repeatability of interfaces between subsystems. The enlarging systems, in which components are used for more than one system require sufficient interface management. A good example was given about the usage of CCTV cameras in a 52 km tunnel project. In the past, CCTV cameras were analog and used for surveillance of the tunnel. Currently the cameras are also used for automated incident detection and are IP-based. This means that two subsystems are now connected and relying on the same camera, but also a network connection is required (IP-based). The enlarging, thus not necessarily technical, interfaces become a challenge here.

From a slightly different technical perspective, complexity is slowly rising. With regard to overarching aspects (like RAMS and cyber security), engineering is less straightforward. These aspects are measured as a combination of subsystems and therefore require more coordination. More structure and guidance are needed to handle the complex aspects, such that translation to subsystems can be made clear and the requirements are achieved.

Organizational complexity

The sector is heavily influenced by the clients and the innovation cycle that comes forward from this. The cycle described in figure 1 shows how innovation works in the sector. The aim for reducing risk and higher quality by the client are the start of every new project. Market parties try to add value such that the tender might be won. If in the end the added value showed beneficial, this is added to new projects and the cycle start again. In this way, innovation grows during and by every new project.

A remark with this cycle is that it is mainly focused on technical solutions and not necessarily aimed at organizational and/or engineering techniques. This is left at initiative of the market parties, as long as they deliver a quality project.

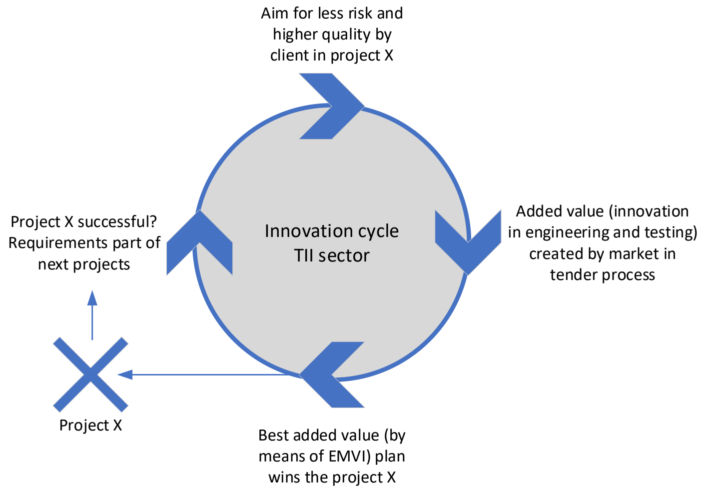


Figure 1 - Innovation cycle

Looking from an organizational perspective, the project structure of companies determines in essence the way how projects are setup. As with Siemens Mobility (where this research was conducted), the structure of the company is based on projects. For every project, a new ‘‘small’’ business is created. In that way, almost every project is unique (from client perspective as well) in team, working method and size. This reduces the learning abilities and standardization development of processes. Every project starts almost from scratch again and scalable economies are lost [20]. Comparing this with matrix structure companies, duplicated work is more common and work is organized in a ‘’factory type’’ setting.

Besides, the internal organizational structure internally, also the contract (origin at the client) does determine a level of complexity. In larger projects, the division of subsystems into multiple contracts, implies an integration to a higher level. The integration is not only internally in those cases, but between companies. This increases chance of mistakes and possible misalignment.

Institutional complexity

Complexity described above closely relates to regulations and standards that are developed for the sector by initiative of clients. A good example is the 3B building block, in which production-, test-, developing street and service are standardized for a certain range of bridges aimed at industrial automation. These regulations become more detailed last years and not necessarily increase complexity. It does add more specific requirements to a project compared to earlier projects.

The standardization flow of clients does influence how engineering will look like in the future. The aim of Rijkswaterstaat is to standardize their projects, such that it positively affects the costs, sustainability, predictability and reliability [2][21][22]. Also ProRail does standardize, with an object type library (OTL) in which every object is described and how it relates to others [23]. This library aims to standardize the communication lines between parties, such that for every component it is clear what is meant and misalignment might be reduced [23]. Also concepts as parametric/generative design could enhance the sector, such that reusable and faster engineering is possible with the same or higher quality [21].

In previous sections it has been discussed already, but the focus towards the TII sector is growing [24]. Standardization, but also automatization, distance control and predictive maintenance are important pillars for Rijkswaterstaat. From their perspective standardization is used to reduce complexity [21][25]. But also in relation to future trends as automated driving, the role of infrastructure might become even more important.

Interviews

In the step that followed, extensive in depth interviews were conducted with lead engineers. The interviews were analyzed on basis of six engineering challenge levels, to understand future engineering and difficulties of previous projects. The six levels are: organization, technical, process, individual, environmental and digitalization. The engineering level topics were transformed to needs, that are used as the requirements for the framework design and implementation process in the following sections.

Framework design

After the interviews with engineers, a framework was developed that consists of eight main building blocks. Each of these blocks describe a component of the department environment (environment in which a department models its subsystem to a certain generic level). For every project, the department environment will be the start and worked out towards a project environment with the project specifics. The building blocks that are designed and needed and guide to process are:

1. Project division
2. Roles and individuals
3. Interactions (process description)
4. Phase distinction
5. Location and storage
6. One-time activities
7. Requirements
8. Filtering

In each of the building blocks, an important element is discussed for structuring the MBSE engineering process. **Block 1** (figure 2) describes the relevant technical subsystems, disciplines and aspects that come together. Where purely technical interactions come together on the top, the aspects with relation to the subsystems indicate engineering boundary conditions. When the subsystems do not meet the conditions, the system delivers not what is wanted. Block 1 provides the initial structuring on which next steps will be built.

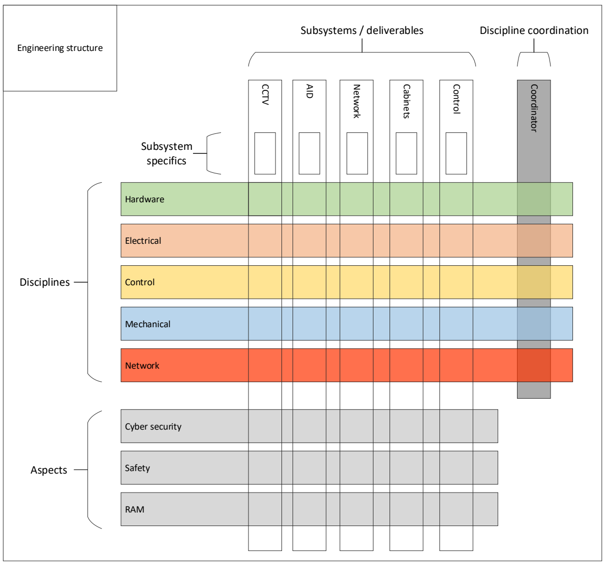


Figure 2 - Division overview

In **block 2** the organizational structure is described, which can be extended to project specifics as well. It indicates who is responsible for what elements and what external parties are involved. Not only the lead engineers for subsystems are depicted, but also for the disciplines and aspects. The second part of this block contains a role division to process steps made in block 3. The roles are again linked to the project team individuals. In that way a clear indication on what responsibilities and tasks the individuals have can be depicted.

In **block 3**, the process for each subsystem are constructed. For example the CCTV system is modelled in all three engineering phases with relations to other subsystems. In that way, the engineers always have a guidance tool for engineering and directly can see implications of their change(s). An important division must be made here. On one hand the development of technical models, and on the other side corresponding process models. In the process models, the process towards technical choices and interactions are described. In the technical modelling, the actual technical products are described with the interfaces to other engineered products. In this way, systems are not only technically linked, but also the processes in different phases. This reduces the need of change meetings, engineering choices and methods to work faster and more effective.

As mentioned already in the section above, the phases are an important aspect in engineering, especially in the Netherlands. In **block 4**, the phase division is incorporated in blocks 3, such that a clear indication of work needed per phase is developed. This mostly relates to the process modelling, in which general choices must be made, that in the final phases result in technical models/products.

In relation to the process in block 3 as well, **block 5** indicates the location and tooling of technical engineering in certain process steps. This helps to indicate where documents are stored and/or what tools are used for developing the systems. The modelling characteristics are important when a central model is used and an indication of location and information must be provided to all users. An indication is given in figure 3.

A block that is related to continuous updating and storage is **block 6**. Here all activities are stored that are required to engineer the subsystems. What is required to be analyzed before the start of a certain engineer phase or during engineering a checklist might be introduced before continuing to follow up steps. Creating an inventory for these activities will reduce the ‘’new’’ work at projects, since it adds to the lessons learned from previous work. This also contain proof of concepts or testing results.

In line with the previous block, this also relates to the interfaces (requirements). Currently the interfaces are stored and processed project specific, but to certain extend, interfaces can be made generic. Doing this in **block 7**, a generic set of interfaces can be used at the start, or transformed into automated files/systems such that attention shifts to project specific interfaces. These interfaces can be stored also for data analysis and assist in making the right choices in the engineering process.

As a final **block 8**, the feature of filtering is an important aspect. During engineering and with a MBSE environment, filter (view) options are convenient to filter to a certain phase, disciplines, individual, subsystem or company. In that way, the individual will exactly know and see where it stands without an information overload. In project environments this is mostly used, such that overview can be maintained.

Combining these eight blocks will assist in engineering following the MBSE methodology. To arrive and setup the models, a concept implementation strategy is proposed in the following section. At the end of this paper, the implementation process is depicted with the framework blocks implemented. It provides an indication on how the process and framework aim to work.

Implementation process

To arrive at the first department environments, a ‘’roadmap’’ is designed. Next to the roadmap, also other factors are discussed with the aim of supporting the new MBSE environment from other perspectives.

From the basic blocks described above towards a generic department environment, multiple steps are required (see process end of this paper). Training in modelling, awareness of the benefits of MBSE and developing agreement on usage and the development. These important factors play an important role at the start of the first development projects. To start such a project, a selection of (less) experienced (lead) engineers that engineer CCTV subsystems come together and design the department environments. Doing it together enhance the generalizability and quality of the models. When finished, a project shall determine the success and therefore also feedback loops are incorporated to keep the environment up to date. If the project turns out positive (financially, technically, usability and in time), the choice is made to further develop more subsystems until all are modelled and coupled to each other. Modelling all system has to most benefits, since then all systems can be linked and no other engineering methods are needed.

With regard to the department environments, having maintenance and guidelines for usage are important. A product owner should be appointed to conduct maintenance, training and determines the usage and guidelines. For the specific project wherein the environment is used, a functional admin will be responsible for project specific content such that it assists in engineering.

When new innovations or subsystem are developed, the choice is made to change this before a project. For the updating of the department environment several update principles are designed:

- Focus on having a minimum of alternatives in subsystem designs
- Department environment grows before projects
- Project environment grows during a project continuously
- Learning of others is equally important as the development of the environments.

Usage of the environment is also determined by multiple project characteristics. When a project is relatively small and experience in the team is high, it might be financially beneficial to engineer following current methods. Mainly with large projects (technical systems scope or actual project size) the need for more control arises and the environment is an addition. The project specifics are summarized in short in figure 4.

Project characteristics determining usage:

- Size of project
- Contract scope
- Team size (large vs small)
- Experience level in team
- New innovation system/subsystem or known subsystems
- Project manager or client

Figure 3 - Project characteristics

Beside mostly internal actions, also external factors were researched. The TII sector works for clients as Rijkswaterstaat and municipalities (mostly governmental) that tender the projects. Creating more room for innovative technical systems is widely accepted, but having innovative engineering methods are left at initiative of the market. In future project, complexity might rise and therefore also new engineering methods that go over company borders have to be introduced. Creating space for these innovations from a client perspective is important without telling companies exactly what to do.

Feedback

After the design of the framework and implementation process, a feedback session was held. From this session, two main points came forward that were implemented in the design of the components, such that it fits the purpose better.

- Project based development not preferable, engineers do have time shortage. Development on basis of engineering groups and outside of projects will results in better models and agreement.
- Unique level is a difficult item for development of MBSE. It seems achievable, but the interviewee does see some challenges here.
- Project division (block 1) is already a good indication of responsibilities and structure, even outside of MBSE.

5. Discussion

The findings of this study clearly showed that the MBSE methodology fits the sector and that application has wide benefits. The framework for development is constructed based on the needs and goals of engineers in the field that also noticed the added value. Although it must be noted that current system do not steer towards chaos or out of control, the future is becoming more complex. The large amount of subsystems and aspects can easily rise out of control. The proposed engineering methodology and framework assist in this development well. The TII sector is changing and engineering methods become more important with learning capabilities in and between projects.

From a client perspective, in which more is demanded from market parties, also more room and freedom should be provided to cope with these changing environments. The results question that SE might not be optimal for developing software related environments. TII projects remain unique to a certain level and capturing the generic part might become a challenge. The practical case on implementing and execution of a modelling environment is not tested, and therefore more research is required to clearly define the advantages and disadvantages of implementation.

The research was mainly focused on engineering processes related to Siemens Mobility. This can cause a bias towards their processes and habits, since also the framework is based on Siemens engineers needs. A wider and more complete analysis of the TII sector should provide more generalizable results.

A final limitation of the study also relates to an important actor in the project, namely the civil engineering partner. Although the interactions with the civil partner can be modelled, the actual influences are not researched in full extend. The developments and innovations in BIM and the interaction between BIM and MBSE shows benefits when used correctly.

6. Conclusion

As described the MBSE was emerged in the product development sector, and MBSE was still limited described and used in the TII sector. The sector is becoming more complex with overarching aspects and larger amount of interconnections and interfaces. The future of TII projects and what developments will evolve were discussed. Followed by the eight building blocks, that assist in developing the generic department environment on which projects can be engineered in MBSE. With the changing engineering environment (client), changes and engineering are central and should be clear to all team members. The uniform way of engineering does create room for innovation and learning, wherein the framework assists in setting up together with the implementation process concept described.

7. Further research

For further research two main topics can be addressed. From a scientific perspective MBSE was proven in other sectors, but full implementation has not been tested in this sector. More research on whether MBSE actually is beneficial and becomes a tool for engineering in this sector is important. Also certain projects seem too small, in which MBSE becomes economically less attractive. The actual thresholds for this boundary could indicate when to and when not to use MBSE. Besides, the process and framework designed should guide the process in the right way, and the only way to test is in practical.

Next to that, also a wider scope of research is required. In relation to the civil engineering partner, client and subcontractors more research should provide an overview on how to strategically implement the MBSE methodology which turns out beneficial for all.

8. Literature

[1] Rijksoverheid. (2018). *Minister van Nieuwenhuizen zet in op forse opknapbeurt oude bruggen en tunnels*. Attained on 20 February 2018 from: https://www.rijksoverheid.nl/actueel/nieuws/2018/01/17/minister-van-nieuwenhuizen-zet-in-op-forse-opknapbeurt-oude-bruggen-en-tunnels

[2] Rijksoverheid. (2019). *Toekomstige opgave Rijkswaterstaat: Perspectief op de uitdagingen en verbetermogelijkheden in de GWW-sector*. Attained on 8th of July 2019 from: https://www.rijksoverheid.nl/documenten/rapporten/2019/06/11/toekomstige-opgave-rijkswaterstaat

[3] Estefan, J. A. (2007). Survey of model-based systems engineering (MBSE) methodologies. *Incose MBSE Focus Group*, *25*(8), 1-12.

[4] Madni, A. M., & Purohit, S. (2019). Economic Analysis of Model-Based Systems Engineering. *Systems*, *7*(1), 12.

[5] Friedenthal, S., Moore, A., & Steiner, R. (2014). *A practical guide to SysML: the systems modeling language*. Morgan Kaufmann.

[6] Van Aken, J. E. (2005). Valid knowledge for the professional design of large and complex design processes. *Design Studies*, *26*(4), 379-404.

[7] Clarkson, P. J., Simons, C., & Eckert, C. (2004). Predicting change propagation in complex design. *Journal of Mechanical Design*, *126*(5), 788-797.

[8] Azhar, A., Gralla, E. L., Tobias, C., & Herrmann, J. W. (2016). Identification of subproblems in complex design problems: a study of facility design. *ASME Paper No. DETC2016-60397*.

[9] Pennock, M. J., & Wade, J. P. (2015). The top 10 illusions of systems engineering: A research agenda. *Procedia Computer Science*, *44*, 147-154.

[10] Fosse, E. (2011). Model-based systems engineering (MBSE) 101.

[11] Browning, T. R. (2001). Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *IEEE Transactions on Engineering management*, *48*(3), 292-306.

[12] Browning, T. R. (2002). Process integration using the design structure matrix. *Systems Engineering*, *5*(3), 180-193.

[13] Danilovic, M., & Browning, T. R. (2007). Managing complex product development projects with design structure matrices and domain mapping matrices. *International journal of project management*, *25*(3), 300-314.

[14] Nagel, R. L., Stone, R. B., Hutcheson, R. S., McAdams, D. A., & Donndelinger, J. A. (2008, January). Function design framework (FDF): integrated process and function modeling for complex systems. In *ASME 2008 international design engineering technical conferences and computers and information in engineering conference* (pp. 273-286). American Society of Mechanical Engineers.

[15] Eppinger, S. D., & Browning, T. R. (2012). *Design structure matrix methods and applications*. MIT press.

[16] Wong, S. S., & Burton, R. M. (2000). Virtual teams: what are their characteristics, and impact on team performance?. *Computational & Mathematical organization theory*, *6*(4), 339-360.

[17] Li, W. D., Lu, W. F., Fuh, J. Y., & Wong, Y. S. (2005). Collaborative computer-aided design—research and development status. *Computer-Aided Design*, *37*(9), 931-940.

[18] Montali, J., Overend, M., Pelken, P. M., & Sauchelli, M. (2018). Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, *14*(1-2), 78-94.

[19] Turner, R. (2007). Toward Agile systems engineering processes. *Crosstalk. The Journal of Defense Software Engineering*, 11-15.

[20] Shaw, E. (2015). Three types of project management organizations.

[21] RWS NEXT, (2018). *RWS NEXT bouwstenen, inspiratie voor de organisatie koers 2020*. Attained on 27th of May 2019 from: https://www.rijkswaterstaat.nl/over-ons/contact/rws-next.aspx

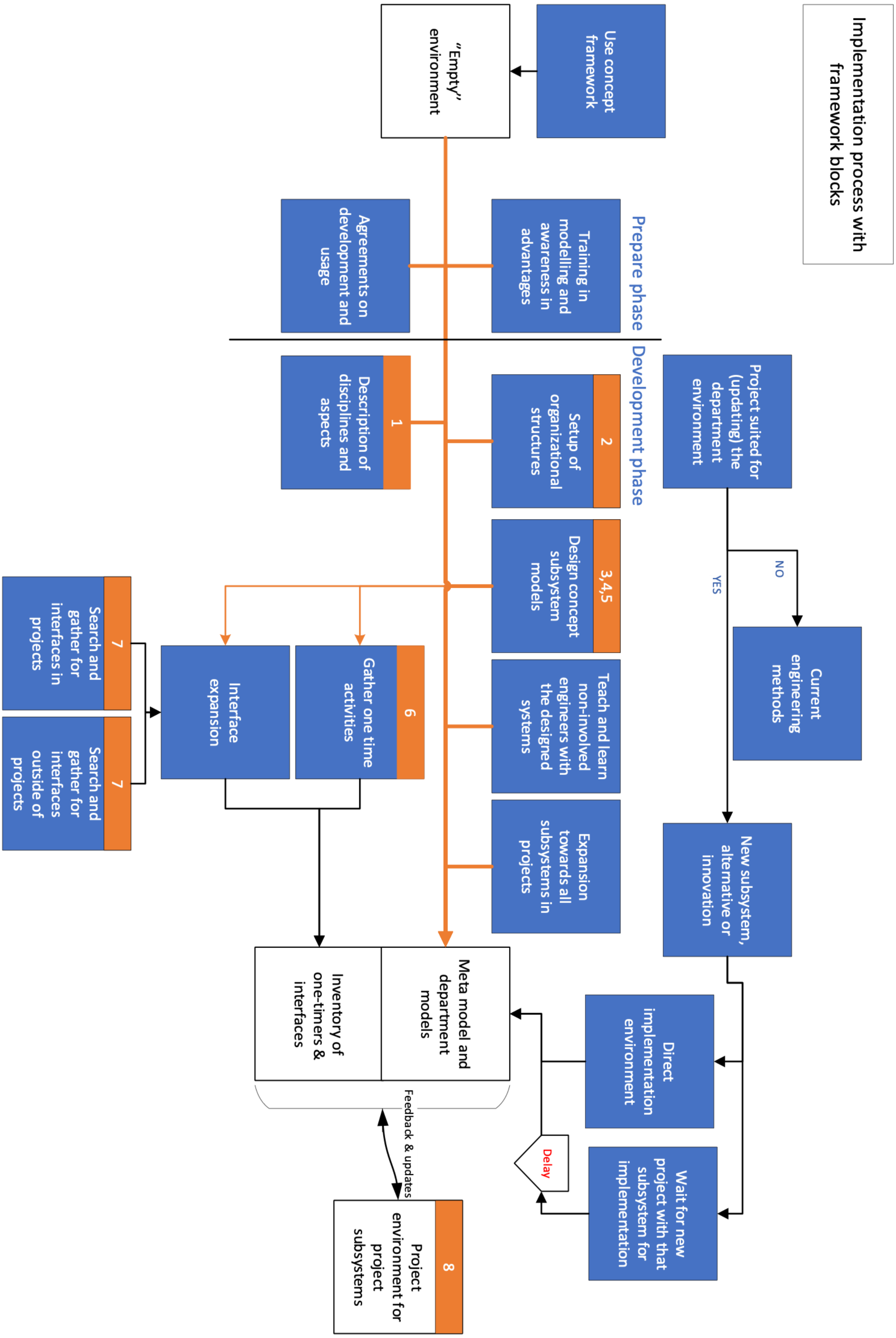
[22] Rijkswaterstaat, (2017). *I-strategie werkwijze informatie voorziening.* Attained on 7th May 2019 from: https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/werkwijzen/werkwijze-in-iv/index.aspx

[23] ProRail. (2016). Objecttype bibliotheek spoor: een taal spreken. Attained on 6th May 2019 from: https://www.spoordata.nl/project/objecttype-bibliotheek-spoor-%C3%A9%C3%A9n-taal-spreken

[24] Rijksoverheid. (2018a). *Ontwikkeling 3B Tunnels.* Attained on 30th April 2019 from: https://www.rijksictdashboard.nl/projecten/592229

[25] Uijttewaal, L. (2018). *Rijkswaterstaat vangt functionele ketens in gestandaardiseerde bouwblokken*. Attained on 7th May 2019 from: https://werkenbij.rws.nl/over-rws/onze-collega/leonuijttewaal/lead-architect-industri%C3%ABle-automatisering.

[26] Baccarini, D. (1996). The concept of project complexity—a review. *International journal of project management*, *14*(4), 201-204.


Implementation process with framework blocks
Use concept framework
"Empty" environment
Prepare phase
Training in modelling and awareness in advantages
Agreements on development and usage
Development phase
Project suited for (updating) the department environment
NO
YES
Current engineering methods
New subsystem, alternative or innovation
1
Description of disciplines and aspects
2
Setup of organizational structures
3,4,5
Design concept subsystem models
Teach and learn non-involved engineers with the designed systems
Expansion towards all subsystems in projects
6
Gather one time activities
Interface expansion
7
Search and gather for interfaces in projects
7
Search and gather for interfaces outside of projects
Meta model and department models
Inventory of one-timers & interfaces
Direct implementation environment
Wait for new project with that subsystem for implementation
Delay
Feedback & updates
8
Project environment for project subsystems