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An Improved Systems Design Workflow for the Case Company

A Proposal

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PREFACE

This thesis stems from my genuine interest in improving our way of working at the case company. Since the beginning of my position as a Mechanical Engineer at the case company, I often found myself wondering how our daily design process can be optimized. This project not only provided me with an opportunity to explore deeper into those improvements but also to learn more about the discipline of industrial management that has increasingly captivated my interest.

The work presented here includes analyzing the current systems design process, collecting insights and perspectives via interviews, and mapping out a more structured and streamlined systems design workflow. The most challenging but rewarding parts of this work were extracting good ideas from various discussions and shaping them into a coherent, and structured proposal that defines the roles and responsibilities, as well as information flow during systems design activities.

I would like to express my gratitude to all those who supported me during this journey. I am especially grateful to my thesis advisor, Dr. Thomas Rohweder, for his invaluable guidance and encouragement, and Mrs. Sonja Holappa, for providing extremely beneficial writing advice. Also, I wish to thank Dr. James Collins for providing profound perspectives for better proceeding with the thesis. Furthermore, I would like to thank my managers, supervisors, and colleagues at the case company who made this study possible with their motivating input and active collaboration in the data collection stages. Finally, I thank my friends and fellow students whose support and presence made this journey more enjoyable.

I hope this thesis will serve as a beneficial contribution to the company’s ongoing development of its design processes and help its efforts to make better products and more effective working practices.

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Abstract

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This thesis is carried out for a case company which leads in developing advanced Carbon Nanotubes (CNTs) and reactors for semiconductors, automotive, and medical diagnostics applications. The objective of this study is to improve the systems design workflow for developing CNT production equipment at the case company.

The methodology is based on Applied Action Research and the study is performed in four main steps including current state analysis to find out the strength and weaknesses of current workflow, literature review for creating a conceptual framework for improving the weaknesses, initial improved workflow proposal, and in the last step, feedback validation of the results and proposing the finial improved workflow.

The current state analysis through interviews with different stakeholders revealed that there are weaknesses in two categories including design data flow management issues, and practical and behavioral issues. The study focuses on the first category and an extensive literature review identifies six approaches for improving the revealed weaknesses. Also, improvement ideas from various stakeholders are collected and considered.

The outcome of this study is a proposal for an improved systems design workflow for the case company which is validated through feedback from higher managers of the company. The proposal is found to be relevant and ready for gradual implementation. The next practical steps are also suggested at the end of the thesis report.

Keywords: Workflow Improvement, Systems Design Workflow, Product Development

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List of Abbreviations

API	Application Programming Interface
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAPA	Corrective and Preventive Actions
CFD	Computational Fluid Dynamics
CNT	Carbon Nanotube
CSA	Current state analysis
CVD	Chemical Vapor Deposition
EIA	Electrical, Instrumentation, and Automation
EUV	Extreme Ultraviolet
EWF	Engineering Workflow
FAT	Factory Acceptance Tests
HAZOP	Hazard and Operability Study
I/O	Input/Output
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
IP	Intellectual Property
PDM	Product Data Management
R&D	Research and Development
RACI	Responsible, Accountable, Consulted, Informed
RAM	Responsibility Assignment Matrix
SAT	Site Acceptance Tests
WFM	Workflow Matrix

1 Introduction

System design is the process of determining and structuring the architecture, components, interfaces, and flow of materials, energy, and data in a system to serve specific functions. It is an important procedure in engineering and product development, ensuring that sophisticated systems are designed to be efficient, scalable and reliable. The complete understanding of technical requirements, functional characteristics, and interdependence between components of a system is essential for effective system design. Ferrari and Sangiovanni-Vincentelli (1999)

The Workflow Management Coalition WFMC (1999) defines the workflow as "the automation of a business process, in whole or part, during which documents, information or tasks are passed from one participant to another for action, according to a set of procedural rules."

A system design workflow specifies the sequence of activities, the framework for decision-making, and the tools used to direct the system design process from the conceptualization generation to implementation. This workflow includes steps such as requirement specifications, concept creation, prototyping, testing, and verification, which are systematically outlined and synchronized with project goals. A well-defined system design workflow reduces inconsistencies, enables clear communication among stakeholders, and provides an effective way to manage the complexity of the systems. Structuring and following a robust system design workflow is crucial for companies that are intensively driven by technology to speed up innovation, reduce costs, and deliver high-quality products. (Collimator, 2022)

1.1 Business Context

The case company of this study is a global leader in developing advanced Carbon Nanotubes (CNTs) and reactors for applications such as semiconductors, automotive, and medical diagnostics. The term “Advanced CNTs” refers to longer, and cleaner CNTs that offer superior optical properties, and electrical and thermal conductivity. Their CNTs are used in Transparent heaters for de-fogging and de-icing of car headlights and cameras, Extreme Ultraviolet (EUV) pellicles in semiconductor production, and Electrochemical sensors for medical diagnostics

The company is based in Finland and has over 130 employees with various backgrounds and expertise in nanotechnology, chemistry, engineering, and business.

1.2 Business Challenge, Objective, and Outcome

The case company requires better systems design workflow. Systems design includes optimizing the processes, components, and controls required for efficient carbon nanotube production equipment. Its legacy practice has been based on project definition instead of a product-centered approach. The current approach suffers from inconsistency, and unclear decision-making processes which are costly and use the resources inefficiently.

The objective of this study is to improve the systems design workflow for developing CNT production equipment at the case company. The outcome of the study is a proposal for an improved systems design workflow which aims to improve inefficiencies and shortcomings of the current approach in the case company.

1.3 Scope and Outline

This study only covers the analysis of the current systems design workflow at the case company and develops a proposal for an improved workflow. The implementation plan and results of the workflow are beyond the scope of this thesis report.

The study comprises of 7 chapters. In chapter 1, in addition to the definition of the system design and its workflow, the business challenge, the objective, and the outcome of the study are described. Chapter 2 outlines the project plan, and data collection process, and explains the reasoning behind the chosen research approach. The current state of the systems design workflow in the case company is discussed in chapter 3. In chapter 4, a detailed literature review on the best practices for system design workflow in industries and possible workflow improvement ideas is presented. Furthermore, a conceptual framework for the workflow proposition is presented. Chapter 5 presents the initial proposal for the improved system design workflow. The feedback received regarding the initial proposal and the final improved workflow is presented in chapter 6. Conclusions and discussions regarding the project and the next practical steps are presented in chapter 7.

The following chapter outlines the project plan and explains the methodology and data collection procedure of the research.

2 Project Plan

The business challenge, and the objective and outcome of this study were described in the previous section. In this section, the selected research approach, the research design, and the plan for collecting and analyzing data are presented.

2.1 Research Approach

In any research work, the method or approach of conducting the research is a critical factor that affects the accuracy and credibility of the results. Hence, it is important to select the correct research approach to ensure the reliability of the proposed solution.

There are two approaches for conducting research comprising Basic or Fundamental research and Applied research. Basic research aims to develop new knowledge and theoretically understand the problems and phenomena. It is mostly used in universities as the result of an academic agenda and in a long-term perspective. The practical aspect of the results in basic research receives relatively little attention. Applied research, on the other hand, deals with real-world problems and seeks immediate practical solutions. Applied research includes various approaches such as evaluation research, research and development, case study, and action research. Action research can be done in different ways. However, they all share the characteristics of continuous improvement iterations. The key difference between basic and applied research is that the basic research addresses universal problems and unknowns whereas applied research focuses on specific issues, for instance in an organization. (Hedrick et al., 1993; Saunders et al., 2023, p. 10).

Applied action research integrates development and investigation, focusing on creating practical, actionable solutions for organizations. It is employed within organizations to drive continuous process improvement by interacting directly with the individuals involved in the process. (Kananen, 2013).

In another perspective, there are quantitative and qualitative types of research. Quantitative research is based on measuring quantity, or amount in the phenomena that can be expressed as quantity. Qualitative research, in contrast, focuses on phenomena that are related to quality, or kind. For instance, investigating the reason for human behavior or finding out how people feel or think about a specific subject is considered as qualitative research. (Kothari, 2004).

Considering the abovementioned explanations and the objective of this study that mentioned in section 1.2, the approach for proceeding with the study falls in the domain of applied action research and is carried out as a qualitative investigation.

2.2 Research Design

This study is carried out in four stages comprising current state analysis, literature review, initial improved workflow proposal, and feedback validation of the proposal. The data collection is done in three stages. The detailed research design to achieve the aimed outcome of this study is presented in Table 1.

Table 1. Research Design

Stage	Data source	Description	Outcome
1- Current state analysis	1. Interviews with stakeholders 2. Field notes 3. Company's process map and description draft	Current state analysis of systems design workflow at the case company • Current workflow • Strengths and weaknesses	Summary of workflow strengths and weaknesses
2- Literature review		Ideas on improving systems design workflow from literature • Concerning weakness x • Concerning weakness y	Conceptual framework
3- Initial improved workflow proposal	4. Interviews with stakeholders and company experts	Preparing improved systems design workflow for the case company • Building workflow proposal for improving weaknesses X, and Y	Initial proposal for an improved systems design workflow
4- Feedback validation of the proposal	5. Feedback on the initial proposal in a through interviews and a workshop	Feedback validation of proposed systems design workflow • Ideas for improving the initial proposal	Final proposal of the improved systems design workflow

As shown in Table 1, the study starts with current state analysis of systems design workflow at the case company through interviews with the stakeholders and field notes to obtain an overview of the current workflow and recognize its strength and weaknesses. At the second stage, a literature review is performed to find out the best practices in structuring design workflows and build a conceptual framework to improve the weaknesses in current workflow. The third stage is dedicated to building the initial improved systems design workflow based on the conceptual framework addressing the weaknesses found in the first stage. Lastly, at the fourth stage, the initial proposal is evaluated and validated through feedback from stakeholders, and the final proposal is drafted.

2.3 Data Collection Plan

To achieve the outcome of the study, data collection is needed in different stages. The plan for data collection is shown in Table 2. There are 3 stages for data collection along with the progress in the study including data 1 for analysis of current state of systems design workflow, data 2 for gathering improvement ideas and evaluating the conceptual framework, and data 3 for validating the initial proposal and drafting the final proposal for improvement of systems design workflow at the case company.

Table 2. Data collection plan

Data Stage	**Content**	**Source**	**Informant**	**Timing**	**Outcome**
Data 1 Analysis of current state of workflow	• Current workflow • Strengths and weaknesses	• Interviews with stakeholders • Field notes • Company's process map and description draft	• VP manufacturing equipment • Head of systems engineering • Head of CAD/CAE • CNT Core Engineer • Sr. EIA Project Manager • Engineers	January	Summary of workflow strengths and weaknesses
Data 2 Improving workflow	• Building workflow proposal for improving weaknesses x, and y	• Interviews with stakeholders and company experts	• VP manufacturing equipment • Head of systems engineering • Head of CAD/CAE • CNT Technology Core Engineer • Sr. EIA Project Manager	March	Initial proposal for an improved system design workflow
Data 3 Feedback validation of proposed workflow	• Ideas for improving the initial proposal	• Interviews with stakeholders • workshop	• CEO • VP manufacturing equipment • Head of systems engineering • Head of CAD/CAE	March - April	Final proposal of an improved system design workflow

As shown in Table 2, the source of data stage 1 revolves around the interviews with the stakeholders and experts in addition to field notes during the investigation of current workflow. In addition, an equipment development process map and description draft which is prepared as a PowerPoint document by the company is investigated. The interviews are based on structured questions and recorded as videos with the permission of the interviewees. The informants are selected based on their role and involvement in the systems design and development processes. The data stage 2 is carried out through interviews with the stakeholders and the company experts to review the results of current state analysis and the conceptual framework obtained from literature review. The outcome is the Initial proposal for an improved system design workflow. After drafting the initial proposal, data stage 3 is caried out through interviews and a workshop with the managers to collect their comments and feedback regarding the initial draft and use them for finalizing the proposal.

The following chapter presents the results of current state analysis of systems design workflow at the case company.

3 Current State Analysis of Systems Design Workflow at the Case Company

In this section, the result of investigating current state of systems design workflow at the case company is presented. It covers the strengths and weaknesses of current workflow and provides a basic description of workflow stages followed by a visualized map of existing unstructured workflow. The data collection process for achieving a better understanding of current workflow, as it was introduced in the previous section, is also described.

3.1 Overview of Data 1 Collection

The objective of this stage is to achieve a clear understanding of the current systems design workflow. The case company is focused on advancing the quality of the produced CNT and developing the capability of delivering CNT with compatible characteristics to the requirements of different applications such as transparent heaters and touch sensors, EUV pellicles for semiconductor industries, and electrochemical sensors for medical diagnostics. Therefore, there is a continuous need for designing new equipment and systems which are safer and more efficient in the synthesis of CNT. This necessitates a practical systems design workflow that is optimized according to the complexity of the design process and could mitigate the risk of functionality issues, safety concerns, and industry standards incompliance, while reducing the cost of reworking.

Current state analysis (CSA) is a crucial stage in any effort for improvement of the practices in organizations and it can be performed through investigating the existing processes and clarifying the problematic areas. A reliable method to conduct the investigation is to discuss with the stakeholders and personnel that are directly involved in the processes and practices. Therefore, structured interviews were conducted with informants inside the case company. They were invited to an online meeting to respond to the prepared questions. The meetings were recorded with the permission of the interviewees and transcribed. As an additional data source, the author’s observations of the daily activities related to systems design were recorded as field notes. Furthermore, an equipment development process map and description draft provided by the company were investigated (Production equipment department of the case company, 2025).

The list of interviewed informants, their roles, and their relevance to the systems design are described as follows:

1. VP of Manufacturing Equipment: is responsible for overseeing technical decision-making, project portfolio management, and process development within the production equipment team. He provides expert consultation on technical details, particularly in the semiconductor industry, and makes critical decisions beyond the scope of project managers, such as selecting robotic systems or evaluating cost-benefit trade-offs for equipment investments. In addition to supervising the progress of design tasks and project portfolios, he ensures that priorities are managed effectively to keep projects on track. He plays a key role in selecting subcontractors and suppliers, ensuring they meet quality and operational requirements. Furthermore, he is responsible for establishing and maintaining essential processes to support long-term efficiency and innovation in manufacturing equipment development.

2. Head of Systems Engineering: is responsible for ensuring overall integrity of systems design and overseeing the progress of projects related to equipment development. While acting as a major interface between mechanical design and automation teams, he provides technical leadership and ensures easy cooperation across disciplines. He guides the component selection processes, which ensure alignment with relevant rules, industry standards and functional requirements. In addition to technical oversight, he is also responsible for establishing and developing ways to work within the systems engineering team. This involves defining methodologies, tools, and workflows that improve efficiency and quality. He ensures that systems engineering is effectively integrated into the

broader operations of the company, which contributes to cross-functional alignment and the success of the projects.

3. Head of Computer Aided Design (CAD) and Computer Aided Engineering (CAE): is responsible for overseeing the mechanical design and simulation process, ensuring that systems and equipment are optimized for performance, manufacturability, and compliance with industry standards. During the planning phase, he manages project scheduling, resource allocation, and task coordination while collaborating with cross-functional teams to develop integrated design solutions. In the development stage, he conducts mechanical design reviews, performs Computational Fluid Dynamics (CFD) simulations, and creates PI diagrams to validate system functionality. He also selects components, manages CAD systems, and ensures seamless communication with clients and stakeholders. After finalizing the design, he supports the transition to manufacturing, oversees installations, and provides technical assistance to address any design-related challenges.

4. CNT Technology Core Engineer: is responsible for driving improvements and changes in systems and equipment, ensuring that modifications meet performance and reliability requirements. In the initial phase, he collaborates with design, procurement, and installation teams to define technical requirements and arrange the necessary budget for component ordering. He also schedules testing activities to align with project timelines and resource availability. During the implementation phase, he conducts or supervises tests, analyzes results, and evaluates whether the changes function as intended. If refinements are necessary, he provides structured feedback to the systems and equipment teams to guide further iterations. By ensuring a systematic approach to verification and validation, he plays a critical role in optimizing system performance and reliability.

5. Sr. Electrical, Instrumentation, and Automation (EIA) Project Manager: is responsible for ensuring that electrical and automation requirements are

integrated into machine and process manufacturing. During the project planning phase, he leads key tasks such as material procurement, supplier selection, and documentation preparation for external partners. He also coordinates Factory Acceptance Tests (FAT), Site Acceptance Tests (SAT), Hazard and Operability Study (HAZOP), and Corrective and Preventive Actions (CAPA) while managing project follow-ups, approving bills, and supporting maintenance efforts. In the development stage, he prepares automation specifications, functional descriptions, and risk assessments while overseeing the creation of electrical drawings, component lists, Input/Output (I/O) lists, and safety calculations. He ensures timely procurement of long-lead-time materials and supervises the installation process, troubleshooting technical issues as they arise. He also participates in testing phases, including I/O tests, leak tests, and process evaluations, ensuring compliance with safety standards. Finally, he collaborates with suppliers to finalize documentation and ensures a smooth transition from installation to full operational status.

6. Mechanical Engineer: is responsible for conceptualizing and designing mechanical components, ensuring structural integrity, and selecting suitable materials. During the initial design phase, he collaborates with other team members through periodic meetings to develop an integrated system layout. In the development stage, he creates detailed technical drawings and specifications for manufacturing. He also oversees prototyping, testing, and troubleshooting to refine the design. Additionally, he coordinates with suppliers to source the selected components. After the design and manufacturing phases, he ensures that installations are carried out correctly and provides technical support to resolve any issues that arise.
7. Development Engineer: is responsible for contributing to the design, testing, and optimization of new and existing equipment. During the design phase, he collaborates with project teams to review concepts, provide feedback, and ensure that designs align with functional and operational requirements. He actively participates in prototype construction and

testing, validating performance under real-world conditions. Based on hands-on experience and testing feedback, he identifies opportunities for improvement in design, maintainability, cost-efficiency, ease of assembly, and error-proofing. By proposing and implementing enhancements, he ensures that equipment is optimized for both performance and practicality, supporting continuous development and innovation.

The structured interview questions were briefly about the overview of the workflow, process strengths, weaknesses and bottlenecks, and process map. A sample of the questions include:

1. Can you describe the overall systems design workflow, from start to finish, for a project?

2. Are there any specific steps or processes that consistently lead to successful outcomes?

3. What are the biggest challenges or pain points in the current workflow? (Examples: delays, communication issues, integration problems)

4. How often do you encounter design revisions or rework? What are the main causes?

5. Could you sketch a quick workflow map or walk through the stages?

The full list of questions for CSA is available in Appendix1.

3.2 Description and Illustration of Current Systems Design Workflow

To illustrate the current systems design workflow, the information collected during the CSA interviews, field notes of daily design activities, and the equipment development process map and description draft, were compiled into a visualized flow chart which shows the overall steps followed by stakeholders and designers to build functional and reliable systems and equipment for CNT synthesis. The compiled flow chart is presented in Figure 1.

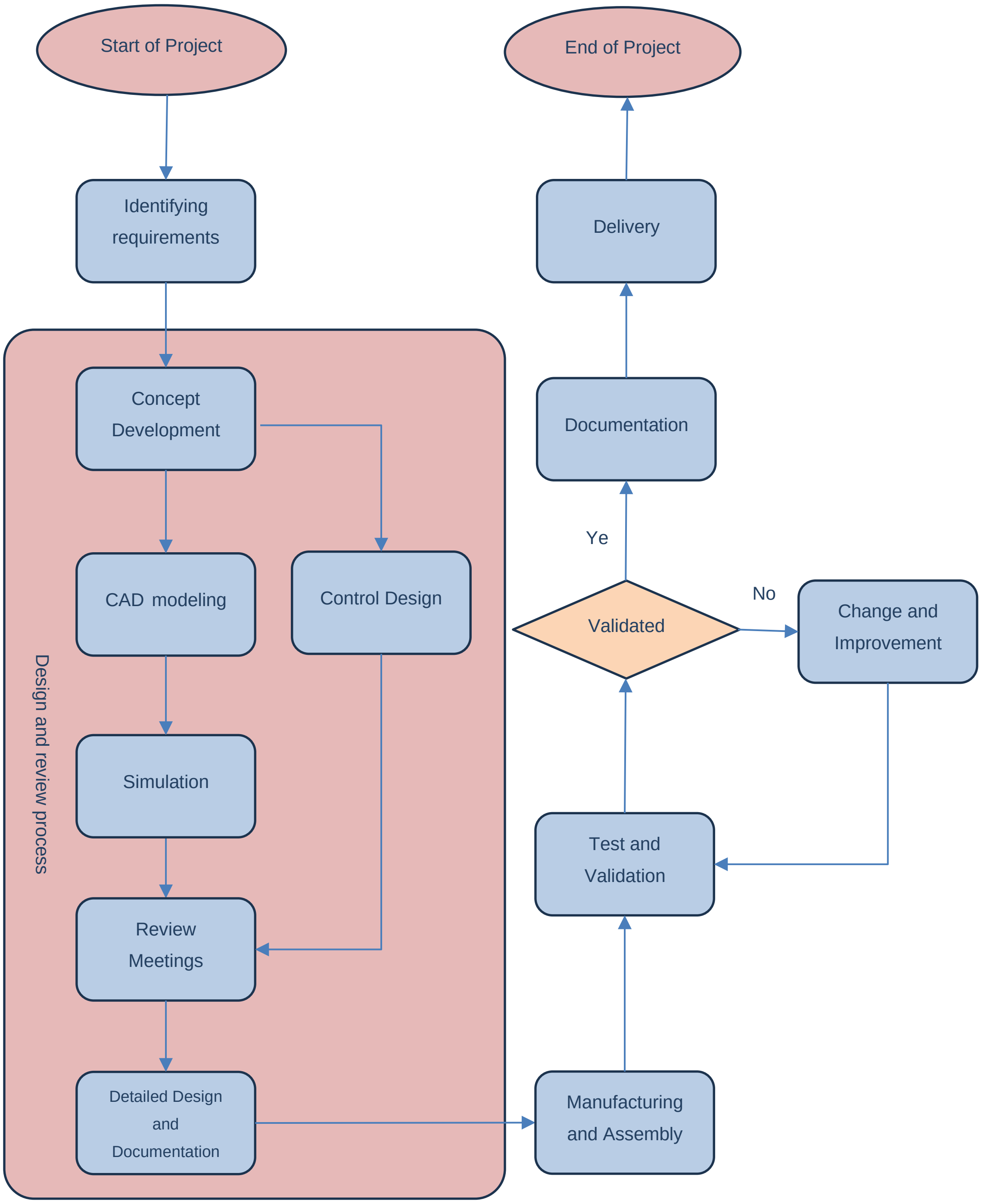

Figure 1. Flow chart of current systems design workflow at the case company

It can be seen in Figure 1 that the current systems design workflow includes various steps and sub-processes such as requirement identification, design and review, manufacturing and assembly, testing and validation, change and improvement, and documentation and delivery. The design and review subprocesses include steps such as concept development, CAD modeling and simulation, control design, review meetings, and detailed design and documentation. Each step is described in the following sub-sections.

3.2.1 Requirement Identification

The technical requirements of the systems must be specified at the beginning of the design process. It means that the expected functionality is described, the inputs and outputs of the system regarding the power, material, and control signal flows are clarified, the dimensional and geometrical restrictions are defined, the compliance requirements with any relevant standard or industry regulation are determined, and the safety concerns are addressed. In addition, if there is any information available about the necessary components, they are listed and the interfaces between the components are specified. At the case company, this stage is carried out in an unorganized way, and it sometimes happens that the requirements are not fully identified at the beginning of the projects.

3.2.2 Design and Review

After specifying the technical requirements of the systems, concept models and control circuits must be prepared by the engineers. Concept models are designed using CAD software and control circuits are either designed by automation engineers or outsourced to the partner companies. Then the functionality of the mechanical models and material flow behavior is simulated by Multiphysics simulation software. The models, simulation results, and control circuits are reviewed in meetings and individual supervisory checks in several tries and when the results are satisfactory, the detailed model and documentation is prepared.

3.2.3 Manufacturing and Assembly

The detailed design documents include commercially available components and custom parts that need to be manufactured. Manufacturing of the custom parts are done by machine shops and partner companies. Custom parts may be built from metals, plastics, ceramics, and other industrial materials. Different manufacturing technics might be needed for each such as machining, welding, sheet metal cutting and bending, and molding. There are different procedures for assembly at the case company. For most of the equipment, the whole package of commercial and custom parts is purchased and manufactured by partner companies, assembled in their premises, and delivered to the case company as a ready product. In specific projects, commercial components and custom parts are procured by the case company, and the assembly is carried out by the technicians in-house. In some cases, a combined procedure is followed, meaning that specific parts are procured by the case company and sent to the partner companies to be used in the final assembly.

3.2.4 Testing and Validation

The manufactured equipment, depending on the complexity of the functions and safety concerns, needs to be tested and validated. Various tests might be needed including mechanical function, automation circuit function, leakage, and particle generation to name as examples. Also, specific tests might be performed on selected components instead of the whole assembly. At this stage, minor or major issues might be found which might necessitate modification of specific components, changing the design of custom parts, changing the automation logic, or even redesigning the whole equipment.

3.2.5 Change and Improvement

When the issues are found in the designed system, change and improvement must be done in an organized manner to be able to trace the evolution of the design. At this stage, the detailed design documents need to be updated or revised. In case of major design changes, new documents with new part numbers are generated. These revised or new documents are used by the technicians in-house to apply minor modifications or sent to the manufacturers again to apply the changes to the custom parts or the whole assembly and deliver the new version to the case company.

3.2.6 Documentation and Delivery

When the functionality and safety of the system is validated and the necessary improvements are applied, the documentation of the design is finalized and stored in the Product Data Management (PDM) system. In addition, all the relevant documents such as safety certifications, user manuals, and components data sheets are archived in the PDM and linked to the design documentation for future reference. Finally, the system is delivered to the facility managers or equipment owners at the case company or the external customers to be operated on their premises.

3.3 Weaknesses of Current Systems Design Workflow

During the interviews for current state analysis, many issues and weaknesses of the current systems design workflow were mentioned by the interviewees. In the following sub-sections, the weaknesses of each stage of the workflow are described. Moreover, the shortcomings in communication and collaboration are presented.

3.3.1 Weaknesses in Requirement Identification

The weaknesses in the requirement identification stage were mentioned by most informants. One of the interviewees mentioned the issue as follows:

> *Poorly defined requirements often lead to scope changes during the project. Also, there is a lack of alignment between customer needs and design outputs. (Informant G)*

Another interviewee highlighted it as follows:

> *Requirements are rarely comprehensive, forcing designers to make unvalidated assumptions and there is no feedback loop to align assumptions with requirements. (Informant A)*

A third interviewee explained this in the following way:

> *Requirements are vague or inconsistently defined, leading to frequent changes during reviews. Also, heavy reliance on project managers, many of whom lack technical expertise, causes problems in specifying the system’s requirements. (Informant B)*

A fourth interviewee mentioned the issue as follows:

> *Requirements are vague, leading to miscommunication and delays. Poor documentation of requirements; scattered across emails, presentations, and informal notes creates a lot of problems. (Informant C)*

The views expressed by the informants regarding this problem indicate that vague or incomplete requirements specification is one of the significant issues. Requirements are rarely comprehensive or specific enough for designers to act on and stakeholders often provide inconsistent or ambiguous requirements. These are costly and lead to frequent changes during the project. The fact that requirements are scattered across emails, meeting notes, or PowerPoint presentations instead of being consolidated into a single document, often forces the designers to make assumptions without validating them with stakeholders. This leads to conflicts later in the process.

In addition, over-reliance on project managers and lack of standard and boundaries were other aspects of the issues regarding requirement identification. Project managers, who often lack technical expertise, heavily dictate requirements and stakeholders and key personnel are not included in the early stages of requirement definition. Also, there is no consistent focus on adhering to industry standards or defining system boundaries. Solving these problems is crucial because they impose delays in achieving consistent functionality of the systems and reduce efficiency of the design process.

3.3.2 Weaknesses in Design and Review Process

Informants also mentioned weaknesses in the design and review process. One interviewee highlighted these issues as follows:

> *There is no formal design process or milestones, leading to inconsistency. Clear definition of roles and responsibilities in the workflow is missing. Also, responsibility for selecting components like actuators and sensors is unclear. Design decisions are often made arbitrarily without proper accountability. (Informant C)*

Another interviewee described the issues as follows:

> *Reviews are sometimes skipped or inadequately conducted. The correct people are not always present in review meetings, and complex issues are often overlooked. Missing files or having outdated files in the documentation system happens occasionally. Finalized revisions are not always tagged or updated as released. (Informant A)*

A third interviewee explained these in the following way:

> *Designers have significant freedom in conceptual design, sometimes leading to misaligned outputs. Reviews do not always address key functional or compliance requirements. The design process is inconsistent, with no clear milestones or gates. Requirements and designs are often rushed due to time constraints. Key documents are often missing or poorly updated, making it hard to track changes or decisions. (Informant E)*

Another issue was also mentioned by a fourth interviewee as below:

> *Reviews often identify significant flaws late, resulting in rework. (Informant B)*

The issues described by the informants reveal that roles and responsibilities in the design workflow are poorly defined, leading to confusion about decision-making authority (e.g., component selection). Also, reviews are skipped or lack the right participants, resulting in missed issues and misalignment. Designers are given excessive freedom in conceptual design, often producing outputs that are misaligned with functional requirements. Reviews frequently identify fundamental flaws late in the process, requiring extensive rework. And most importantly, lack of structured workflow or milestones for the design process, is causing inefficiencies and inconsistent outcomes.

3.3.3 Weaknesses in Testing and Validation

Regarding the weaknesses in testing and validation, the interviewees described the issues as follows:

> *There is no structured process for testing and validating manufactured parts. (Informant A)*

> *System-level testing is not formalized, leading to reliance on field performance to identify issues. (Informant E)*

> *Insufficient focus on testing during assembly and production makes problems. (Informant B)*

> *Testing is often minimal or skipped entirely for individual components. Validation processes for system-level performance are not clearly defined. (Informant D)*

> *Prototypes are often considered as deliverables, leading to rushed testing phases. (Informant F)*

The above-mentioned issues indicate that minimal testing of components, system-level validation gaps, counting on prototypes as deliverables, and lack of formal testing process are the main weaknesses in the testing and validation stage. These show that validation is treated as an afterthought, leading to functionality issues being discovered during field use.

3.3.4 Weaknesses in Design Change Management

Design change management was also found to have weaknesses in the eyes of interviewees as follows:

> *Lack of structured design change management creates confusion and redundant work. (Informant B)*

> *Design revisions are often made without full communication or evaluation. Owners of designs are not always informed about updates, causing discrepancies. (informant A)*

> *Frequent, and poorly communicated changes lead to delays and confusion. (Informant D)*

It can be concluded that unstructured change requests, lack of communication around changes, frequent and redundant revisions, and ownership and oversight issues are the weaknesses revealed by the interviewees. These issues create gaps in alignment and disrupt timelines leading to inefficiencies. Poor coordination of design changes leads to overlapping updates and redundant work. Also, lack of ownership for design change management causes delays and inconsistencies in the implementation of revisions.

3.3.5 Weaknesses in Communication and Collaboration

Weaknesses in communication and collaboration were also mentioned by informants. The interviewees described the problems as follows:

There are no clear communication channels and informal discussions often lead to confusion. Collaboration bypasses official procedures, leading to gaps in oversight. (Informant A)

The new JIRA system is improving communication, but it is not yet fully implemented. Collaboration depends heavily on informal communication methods. (Informant C)

Design change decisions and updates are often not achieved or accessible to all relevant parties. (Informant E)

There is misalignment between the needs of design, engineering, and operations teams and sometimes the stakeholders are not involved in the design change decisions (Informant D)

The above-mentioned responses indicate informal communication channels, lack of stakeholder involvement, poor archiving of information, and not fully implemented emerging tools are considerable issues in communication and collaboration. These issues lead to confusion and cause misalignment between stakeholders. Lack of centralized systems for storing and referencing decisions, designs, and communications lead to untraceable design history and repeating systems functionality issues.

3.4 Strengths of Current Systems Design Workflow

During the conversations with the interviewees, a few strengths were also noticed. Informants A, B, C, and D mentioned that the design team consistently delivers functional systems even though the timelines are tight. Informants A and B noticed that the team demonstrates flexibility to adapt evolving requirements and constraints. They also mentioned that designs and revisions are created quickly when requirements are well-defined. Additionally, informant C, D, and G notified that implementation of JIRA and other tools is gradually improving communication and archiving practices and Informal teamwork often mitigates the impact of unclear processes.

The above-mentioned strengths can be categorized as team resilience, adaptability, fast design cycles, emerging communication improvements, and collaborative efforts.

3.5 Summary of Current Systems Design Workflow Strengths and Weaknesses

The strengths and weaknesses of systems design workflow are summarized as shown in Table 3 and Table 4 respectively. The highlighted, orange-colored weaknesses in Table 4 are the focused ones for proposing improvement approaches.

Table 3. Summary of strengths in systems design workflow

Team Resilience	The design team consistently delivers functional systems under tight timelines.
Adaptability	The team demonstrates flexibility in adapting to evolving requirements and constraints.
Fast Design Cycles	Designs and revisions are created quickly when requirements are well-defined.
Emerging Communication Improvements	The implementation of JIRA and other tools is gradually improving communication and archiving.
Collaborative Effort	Informal teamwork often mitigates the impact of unclear processes.

Table 4. Summary of weaknesses in systems design workflow

Design Data Flow Management Issues	Requirement Identification	Vague or Incomplete Requirements
		Over-Reliance on Project Managers
		Lack of Standards and Boundaries
	Design and Review Process	Unclear Roles and Responsibilities
		Inconsistent or Missing Reviews
		Late Discovery of Flaws
		Lack of a Formal Design Process
	Design Change Management	Unstructured Change Requests
		Lack of Communication Around Changes
		Frequent and Redundant Revisions
		Ownership and Oversight Issues
Practical and Behavioral Issues	Testing and Validation	Minimal Testing of Components
		System-Level Validation Gaps
		Prototypes as Deliverables
		No Formal Testing Process
	Communication and Collaboration	Informal Communication Channels
		Lack Stakeholder Involvement
		Poor Archiving of Information
		Not Fully Implemented Emerging Tools

It can be seen in the Table 3 that there are noticeable strengths in the current systems design workflow and the design team is able to adapt evolving changes to the systems' requirements and deliver functional equipment. Also, there have been continuous improvements in communication and collaboration between the stakeholders and better task management tools and platforms are being implemented. However, there are weaknesses in the design workflow that must be addressed. The weaknesses are listed in Table 4 in two categories comprising design data flow management issues and practical and behavioral issues. In this study, the focus is on finding solutions for improving the design data flow management issues especially on Vague or Incomplete Requirements, Unclear Roles and Responsibilities, Inconsistent or Missing Reviews, Lack of a Formal Design Process, Unstructured Change Requests, and Ownership and Oversight Issues due to their broader impact on the improvement of the systems design workflow by streamlining the major steps and their sequential effect on the improvement of the practical and behavioral issues.

In the next chapter, a conceptual framework is structured for an improved systems design workflow at the case company using ideas from reviewing relevant literature.

4 Ideas from Literature on Improving Systems Design Workflow

In this chapter, a literature review is carried out to find relevant approaches and solutions for creating a conceptual framework for improving the weaknesses of the systems design workflow demonstrated in the previous chapter.

4.1 Formalizing Structure of Workflow

As mentioned in the previous chapter, one of the major issues in the current systems design workflow is lack of a formal design process. In order to create a formal structure for the systems design workflow, three articles were found to be useful as follows:

In the first article, Heejung and Hyo Won (2006) present a workflow structuring process that integrates control flow and data flow modeling. The research focuses on improving the efficiency of the design process by structuring the workflows using a Workflow Matrix (WFM). Major challenges in design processes are complex interdependency, iteration, and data flow conflicts that increase the lead time and make coordination difficult. The authors propose a structured workflow modeling approach to reduce unnecessary iterations, optimize resource allocation and improve decision making. Workflow Matrix (WFM) defines control and data flow between design activities, and the Workflow Structuring organizes the workflow in a well-structured form by identifying unnecessary iterations. They also propose Reengineering Strategies including quantitative approaches that measure workflow complexity and eliminate unnecessary iterations, and the qualitative approach that applies best practices such as overlapping activities, improvement in communication, and assigning cohesive teams. In addition, through a case study of a motor manufacturing company, they show how this methodology reduces design time and improves efficiency. Their research framework is illustrated in Figure 2.

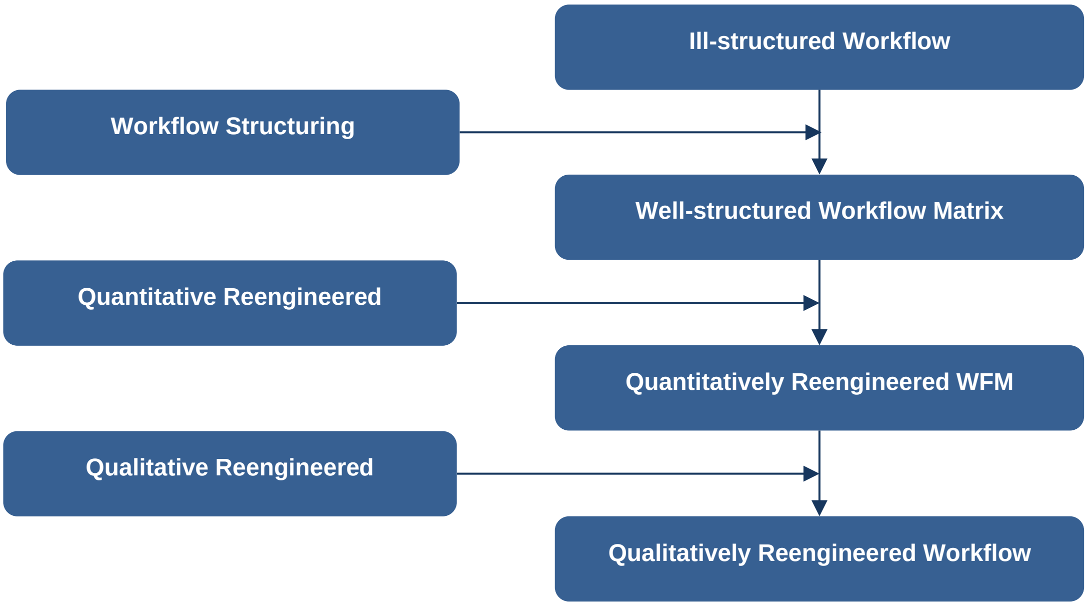

Figure 2. Workflow structuring framework. Mod. Heejung and Hyo Won (2006)

When formalizing the system design workflow for CNT synthesis equipment at the case company, the workflow matrix (WFM) can be implemented systematically through a series of structured steps. First, the major components of the workflow should be defined by identifying the required design activities, such as material selection, CAD modeling and prototype tests. Additionally, the dependence between these activities should be mapped using control flow and data flow rules. Second, WFM should be constructed by developing an incidence matrix in which design activities are represented as rows and columns. Dependence, including iterations and data flow, should be marked using appropriate routing operators, such as Serials, And-Split, Or-Split, And-Join, and Or-Join. Third, workflow must be structured to increase efficiency. This involves identifying and eliminating unnecessary iterations to reduce the design lead time. The workflow should then be refined into a well-structured WFM using structuring algorithms. Finally, reengineering strategies must be applied to optimize the workflow. This involves prioritizing important tasks and streamlining data flow for quantitative improvement. Additionally, parallelizing activities, enhancing team coordination, and managing dependencies effectively, contribute to qualitative enhancement in the design process.

In the second article, Ferrari and Sangiovanni-Vincentelli (1999) examine the principles of system design, emphasizing the separation of functions and architecture. It discusses how platform-based approaches enable software reuse and flexible system integration, eventually contributing to more efficient design workflows. The study recommends adopting modular design principles for equipment design, enabling customization by maintaining a standardized base structure. It highlights several major points about design approaches. Traditional design considers each project as a unique effort, resulting in high cost and long development time, while platform-based design focuses on creating reusable architectures that support several products with minimal modifications. Hardware platforms contain families of architecture that share common constraints, which allow reusing of hardware, while software platforms standardize interaction with hardware through a unified Application Programming Interface (API), simplifying the application development. Together, hardware and software platforms create a system platform, which offers a scalable and reusable design framework. The platform-based design approach provides many advantages, including reduced production and development costs, better flexibility and reusability of components in product generations and a shorter time to market using the existing architectures.

A platform-based approach can be systematically applied to the systems design workflow at the case company through the following structured steps to increase the efficiency and scalability of the design process. First, a CNT synthesis system platform should be defined by standardizing core hardware components such as reactors, gas handling systems, sensors, control units and robot material handling. Additionally, a modular API should be developed to create a strong software platform for process control, automation, data logging, quality control, defect detection, Internet of Things (IoT) integration, and remote monitoring. Second, the design must be modularized to improve reusability. This involves creating hardware and software modules that can be implemented in various CNT production units. For example, a standardized control unit can be used in both prototype systems and large-scale production setups, which improves the design consistency and efficiency. Third, platform-based workflow must be implemented to streamline development. Instead of redesigning the system for each project, a library of reusable modules can be established. A typical workflow can involve selecting a base platform such as a standard Chemical Vapor Deposition (CVD) system, customizing components such as temperature sensors, adjusting the software configuration for specific parameters such as CNT diameter, and deploying the system with AI-driven automation. Finally, cost and performance optimization should be prioritized. Reuse of validated hardware can reduce the cost of engineering, the time-to-market can be shortened through pre-developed software modules, and production flexibility can be increased by enabling rapid modifications and customizations.

In the third article, Heller et al. (2004) explore the challenges of interorganizational design in chemical and mechanical engineering industries. They present the AHEAD workflow management system, especially designed to handle complex, iterative and interorganizational nature of engineering design processes. Traditional project management and workflow systems struggle to manage non-linear, evolving workflows common in engineering, where frequent iterations and external collaborations are necessary. The AHEAD system includes several key features that increase workflow flexibility, collaboration and adaptability in complex design projects. First, dynamic task nets allow workflows to develop dynamically, unlike rigid workflow models. This enables real-time adjustment to accommodate changing project requirements. Second, inter-organizational collaboration provides seamless cooperation between companies by allowing subprocesses to be outsourced while maintaining strict information security protocols. Third, outsourcing and contract management ensures that the tasks assigned to external teams are executed with controlled data exchange, preserving workflow integrity and confidentiality. Fourth, monitoring and feedback mechanisms provide real-time progress tracking and feedback loops, improve coordination and enable proactive decision making. Finally, change protocols support the workflow modifications without disrupting the ongoing processes, ensuring adaptability to evolving project requirements. The article also includes a case study on the design of a polyamide 6 production plant indicating how

AHEAD system improves collaboration, decision making, and adaptability in multi-organizational design projects.

The AHEAD workflow management system can increase the efficiency, collaboration and adaptability of CNT synthesis equipment design workflow at the case company through a structured approach. First, it can be used to define dynamic task nets by identifying major design processes such as reactor type selection, process optimization, component selection, and quality assessment. Flexible workflows are then created, which allow iterative refinements based on the test results. Second, it facilitates inter-organizational collaboration using secure outsourcing and contract-based workflows, protecting Intellectual Property (IP), and tracking responsibilities. Real-time coordination is enabled by suppliers' contributions and syncing updates between engineering and Research and Development (R&D) teams. Third, AHEAD supports continuous improvement through dynamic change management, allowing workflow modifications based on experimental feedback without restarting the entire process. Finally, it enhances decision making with data-driven insights by tracking major performance metrics, automating reporting for faster decision making, and using historical data to optimize reactor specifications and operating settings.

In conclusion, the formal systems design workflow for the case company can be structured by combining various aspects of each approach and benefit from the most relevant part of them. For instance, key design activities and their interdependence can be identified using control and data flow rules, and then the workflow matrix can be structured to increase the efficiency of design processes as demonstrated in the first article. Also, the platform-based design approach from the second article can help to develop modular systems and increase reusability of the designed sub-systems. The principles of the AHEAD workflow management can also be used for structuring a dynamic design workflow and better manage the outsourcing and interorganizational collaborations.

4.2 Organizing Requirement Identification

Rouibah and Caskey (2003) introduce the Engineering Workflow (EWF) system, which is a dynamic and parameter-based approach to managing complex and concurrent engineering design processes. Traditional workflow management systems are often static and sequential, which makes them unsuitable for collaborative, iterative, and inter-company engineering projects. The EWF overcomes these limitations by focusing on parameters, their evolution, and interactions between the design participants. The EWF system provides several major features that improve engineering workflow management. It employs parameter-based design control, tracks important engineering parameters such as dimensions, tolerance and physical properties to ensure real-time updates and synchronization in teams. The system supports a dynamic and iterative workflow, recognizing that design is a non-linear process, and allows for modifications, iteration and flexible task routing. EWF also facilitates collaboration in the supply chain by providing a structured framework for managing supplier and partner contributions and real-time sharing of design changes to prevent conflicts. Additionally, it enhances transparency and change management by tracking parameter development, decision history and interdependence between various design aspects. Finally, the EWF improves the decision-making by allowing teams to make logical early-stage decisions with incomplete information when monitoring the parameter maturity throughout the process.

The EWF approach can be effectively applied to organize system requirement identification for CNT synthesis equipment design. First, it defines major system requirements using parameters by identifying essential engineering factors such as reactor type, gas flow rate, temperature control limits, and catalytic material properties. Initial parameters range are established, which allow for iterative refinement. Second, it creates a dynamic and iterative workflow for requirements validation by specifying parameter dependencies, ensuring consistency in design relationships, and allowing engineers to propose, review, and modify the requirements without disrupting the workflow. Automated notifications keep stakeholders informed about updates. Third, EWF assigns parameter ownership to facilitate cross-team collaboration, where coordinators oversee major specifications, engineers refine values based on experimental data, and reviewers approve changes. It also ensures supply chain integration by linking parameters to supplier-provided materials and maintaining a shared system for tracking updates. Finally, EWF tracks the parameter evolution to make better decisions using maturity levels to differentiate between flexible early-stage estimates and finalized locked-in values. Traceability and accountability throughout the design process is ensured by version control and change monitoring.

4.3 Enhancing Design Change Management

Focusing on knowledge management, Roucoules et al. (2016) emphasize the need to capture the design logic to facilitate design change propagation and innovation. They explore how design can be rational and engineering memory can improve decision making and change management in product design. The study highlights the major aspects of engineering design processes, especially focusing on decision traceability and change management. Engineers often spend a lot of time retrieving previous design decisions rather than focusing on innovation. It is necessary to capture and store the design rationale to improve efficiency in future projects. However, challenges in design change management are due to difficulties in tracking modifications, identifying dependencies, and maintaining consistency, which can increase cost and delay. To address this, a framework for decision traceability which uses the Six W's model (who, what, why, where, when, and how) to document design options is proposed. It captures design routes, modifications and reasoning, and employs traceability layers to link previous decisions with future improvements. This approach provides significant benefits, such as reducing the time spent on information retrieval, enhancing collaborative decision-making, and ensuring faster and more effective adaptation in design changes.

To optimize design change management for CNT synthesis equipment in the case company, an engineering design memory system can be applied through a structured approach. First, it is necessary to capture the design rationale, key decisions related to material options, process parameters such as temperature, pressure, and gas flow rates, as well as equipment layouts and constraints. The Six W’s model shows who made the decision, what was decided, why it was selected, where it affects the system, when it was implemented, and how it was evaluated and validated. Second, a traceability system for change management enables dynamic tracking of modifications by linking design changes to previous decisions and monitoring parameter dependencies, such as how changes in geometry affect CNT uniformity. Smart version control ensures that various designs configurations are stored, providing a clear history of modifications to reduce errors. Finally, decision support for improvement in future equipment is facilitated through AI-Assisted knowledge retrieval, which suggests previous design solutions for new challenges and identifies similar scenarios to guide decision-making. This approach reduces redundant engineering efforts by preventing the repetition of already addressed issues, and accelerates rapid prototyping by reusing validated designs.

4.4 Clarifying Roles and Responsibilities

GräBler et al. (2022) explore how responsibility assignment frameworks can enhance the organization of systems engineering projects. The study highlights the major aspects of systems engineering and complexity management, emphasizing the need for a structured responsibility assignment framework as systems become more complex. The International Council on Systems Engineering (INCOSE) model provides a structured approach by defining input, output and roles within a project. A widely used method for role assignment is RACI (responsible, accountable, consulted, informed) scheme, which clarifies roles and responsibilities in systems engineering projects. Roll-based systems engineering implements this framework by assigning specific tasks to various roles such as System Architects, Technical Managers and Validation Engineer using a Responsibility Assignment Matrix (RAM) to ensure clarity in engineering decision-making and execution. The approach was validated through industrial application in a German automotive company, showing that clear role definitions help reducing project risks and disabilities.

To clarify roles and responsibilities at the case company, the RACI scheme can be applied by establishing clear roles definitions and assigning responsibilities systematically. First, the major engineering roles are defined, including the System Architects, designing the overall CNT production system, the Process Engineer, who develops and optimizes the CNT synthesis process, the Validation and Verification Engineer, who ensures that the system meets performance and quality standards, the Project Manager, who oversees the project timeline and resources, and the Safety Engineer, who ensures compliance with regulatory and safety standards. Subsequently, the RACI matrix is applied to assign responsibilities, as presented in Table 5, ensuring clarity in role distribution. Implementing the RACI framework in CNT Systems Engineering provides several benefits including eliminating confusion by clearly defining task ownership, reducing the project risks by ensuring accountability, improving collaboration between engineering teams, and enhancing efficiency in handling design changes.

Table 5. Example of RACI matrix

Task	System Architect	Process Engineer	Validation and Verification Engineer	Project Manager	Safety Engineer
Design Reactor System	R	C	I	A	I
Optimize CNT Growth Parameters	C	R	C	A	I
Validate System Performance	I	C	R	A	C
Ensure Compliance with Safety Standards	I	C	C	A	R

4.5 Conceptual Framework

According to the reviewed literature and possible steps in utilizing their approaches, a conceptual framework for improving the systems design workflow at the case company can be structured as presented in Table 6.

Table 6. Conceptual framework

Formalizing structure of workflow	Use **Workflow Matrix** and **Reengineering Strategies**. Heejung and Hyo Won (2006). Use **Platform-Based design** workflow instead of projects. Ferrari and Sangiovanni-Vincentelli (1999). Use AHEAD workflow management system. Heller et al. (2004).
Organizing requirement definition	Use **Engineering Workflow (EWF)** and **parametrize requirements**. Rouibah and Caskey (2003).
Enhancing design change management	Use **Engineering Design Rational and Memory** and **Six W's Model** to document decisions and changes. Roucoules et al. (2016)
Clarifying roles and responsibilities	Use **INCOSE model** and **RACI scheme** for systems engineering. GräBler et al. (2022)

In the next chapter, an initial proposal for an improved systems design workflow for the case company using the demonstrated conceptual framework and ideas from the stakeholders collected in Data 2 stage interviews will be presented.

5 Initial Proposal for Improved Systems Design Workflow at the Case Company

This chapter presents the initial proposal for an improved systems design workflow for the case company. The proposal is based on the ideas introduced in the previous chapter as a conceptual framework focusing on improvement of the selected weaknesses, in addition to complementary ideas from stakeholders involved in the data collection stage 2.

5.1 Overview of Data 2 Collection

The objective of this data collection stage is to discuss the weaknesses found in CSA stage, why the focused ones are selected, and the relevance and practicality of the conceptual framework with stakeholders and collect their comments and ideas for structuring the initial proposal of an improved workflow. The data collection is carried out in separate interviews with stakeholders and organized as Microsoft Teams meetings. The meetings were recorded and transcribed for extracting the key points and ideas presented by the stakeholders.

The stakeholders invited for data stage 2 include VP manufacturing equipment, Head of systems engineering, Head of CAD/CAE, CNT Technology Core Engineer, and Sr. EIA Project Manager. The roles and relevance of these interviewees were presented previously in Section 3.1.

5.2 Ideas From Stakeholders for Improving Workflow Weaknesses

During the interviews the organized results of CSA stage for strengths and weaknesses at the case company shared with the informants. Also, the conceptual framework presented to analyze the effectiveness and relevance of the selected approaches on improving weaknesses of the current workflow. The informants confirmed that the focused weaknesses are significant and have a broad effect on improving the systems design workflow at the case company. For instance, informants B and C confirmed the conceptual framework, and the selected issues as follows:

> *This all follows the reality of our everyday problems and work… All the proposed improvements are very relevant… I'm actually quite impressed. (Informant C)*

> *To me it makes sense to focus on design data flow management issues and have it that kind of size that it's within the thesis topic… I think these selected issues are exactly the problems where we need to do something. (Informant B)*

Regarding formalizing the workflow structure, Informant A mentioned the importance of avoiding overly restrictive workflows and allowing flexibility and iteration between steps. Also, he emphasized the need for gradual implementation and focused on small and manageable changes, incorporating a final decision stage after review meetings, integrating feedback loops for revisiting and revising earlier steps, and implementing different review levels such as frequent informal reviews and formal reviews with broader stakeholder involvement. Informant B indicated the importance of incorporating initial steps to define project scope, subsystems, and the use of existing solutions into the workflow, and separating research and development projects from manufacturing and delivery processes for better efficiency. Informant C suggested design change management activities to be treated as an independent process, defining workflow for different types of projects and separating new system design from upgrading old systems, and incorporating iterative loops to reflect the reality of design revisions. Informant D suggested incorporating risk assessment of the projects at the beginning of the design phase and adding steps for procurement and manufacturing to the workflow. Furthermore, all the informants supported the idea of adopting a platform-based design approach and standardization of subsystems. For instance, informants A and B commented as follows:

Totally makes sense... already in the semi 2.0 reactor we are talking about modular design… We would have a catalyst cartridge platform that would easily fit to other reactors. (Informant A)

I think we are trying to move forward to that kind of direction to have qualified and reusable modules with the semi 2.0 project… This direction is very useful and helps with the separation between R&D and delivery projects. (Informant D)

Additionally, Informant B and C mentioned that the platform-based design approach might be partially applicable for a limited number of qualified subsystems and modules at this stage since the systems and equipment at the case company are not fully productized yet.

Platform-based design is something that our company should aim for… We are unfortunately very far from there… we have not yet really made the first product… You need to make the first product, and from there you can start thinking about this more like platform-based design. (Informant C)

We should have qualified components that become like a library or standard component we can use freely… When we get something completed with good results, that should become like a reusable platform module even if a full platform is not feasible yet (Informant B)

For clarifying roles and responsibilities, Informant A supported the use of RACI matrix and emphasized establishing clear decision-making authority and ensuring that topic experts are involved in decision-making processes. Informant B suggested specifying modules and sub-system owners to improve accountability and management. Informant E mentioned the need to clarify the procurement and purchasing roles and responsibility and keeping the team leaders as informed role in every step. Informant D indicated that using RACI matrix is useful for project level roles and responsibilities, however, the job descriptions and responsibilities need to be clearly defined at the company level.

The problem at our company is a bit more widespread than just having a RACI matrix… There's a lot of positions at our company which don't have a description of what they should be doing. They need to be in black and white. (Informant D)

Regarding requirement identification, Informant A mentioned that there is a different point of view in the process development team and the equipment design team. He acknowledged the usefulness of parametric requirement management for the equipment design team. However, he added that the system requirements are not always clear for the process development team at the beginning of the projects. Informant C suggested a metric scheme to clarify requirement identification responsibility. Informant D indicated that parametric approach is rather useful for categorizing the requirements and there needs to be a structured way of identifying requirements in the workflow. Informant B offered multi-level requirement identification as templates for high level goals of the system, process requirements, sub-systems requirements, and then requirements of each component. He explained it as follows:

There is so little experience of managing real equipment products at our company… When there is a request, what are the requirements of the system? So there needs to be established this kind of requirement template that starts from the high-level goals to the middle level or like starting from the total architecture and then going to the component level… (Informant B)

For improving the design change management, informants found the Engineering Design Rationale and Memory and Six W's Model a good idea and added suggestions regarding its practicality. Informant A suggested linking the history of the decisions and the reasons behind the changes to the final design documentation. Informant B offered using Confluence environment for logging the decisions, goals, meeting notes, specs and linking them to the products or sub-systems data instead of project folders. Informant C indicated that change management should be applied not only in the systems design process but also expanded to managing the existing products. He stated his idea as follows:

We should have a change management process in general… it should be applied not only to system design, but also to managing existing products… Change management could work like a plugin to system design but should be a separate entity that requires defined roles and responsibilities. (Informant C)

5.3 Embedding Key Current Strengths into the Workflow for the Case Company

As mentioned in Section 3.4, strengths of current systems design workflow at the case company include team resilience, adaptability, fast design cycles, emerging communication improvements, and collaborative efforts. These strengths can be preserved or even enhanced by incorporating flexibility in the workflow and enabling collaboration and communication through better organized channels. Following the improvement ideas in the workflow for better identification of the requirements and enhancing the design change management by recording the history of the decisions can increase the responsiveness of the design team to evolving requirements and changing requests.

5.4 Summary of Initial Proposal for an Improved Systems Design Workflow

The most important aspects of the weaknesses mentioned by the stakeholders during the data collection 1 and 2 were the lack of formalized systems design workflow and unclear roles or job descriptions and responsibilities of all the stakeholders involved in the systems design process. In addition, issues in system requirement identification, lack of sufficient review meetings, and unstructured design change management were considered crucial. The conceptual framework and co-created ideas for workflow improvement can be summarized as follows:

Frist, using workflow matrix and reengineering strategies to structure the improved workflow, considering separation of R&D and delivery projects, considering separation of new systems design and upgrading existing systems. Also, forming dynamic workflow to cope with evolving requirement as used in AHEAD system, improving requirements identification by applying parametrization and multi-level requirement templates. Additionally, focusing on modular systems to make qualified sub-systems and moving towards platform-based design. Moreover, defining the required roles and responsibilities by new job descriptions and RACI matrix for involved stakeholders, and improving design change management by recording design rationale in an accessible environment. Furthermore, the current strengths of the workflow need to be preserved.

To achieve these improvements, first the required roles and job descriptions are determined in three categories including Application/Customer-Facing Roles, Core Technical Roles, and Supporting Roles shown in Table 7, Table 8, and Table 9 respectively.

Table 7. Application/Customer-Facing Roles

Role	**Job description**
Application Engineer	Works with customers to adapt systems for specific CNT applications such as transparent conductors, CNT membranes, electrochemical sensors Provides technical support and product customization
Field Service Engineer	Installs and maintains systems at customer sites Troubleshoots issues and ensures performance in operational environments
Marketing Manager	Initiates the design process based on customer needs and market trends Defines application requirements and coordinates early-stage input with R&D
Systems R&D Leader	Supervises technical feasibility and project planning Allocates engineering resources and coordinates design execution across teams Analyses design outputs and validation reports

Table 8. Core Technical Roles

Role	Job description
Process Engineer	Designs and optimizes the CNT synthesis process Selects gases, temperatures, catalysts, and flow rates Ensures scalability and repeatability of the synthesis
Mechanical Design Engineer	Designs reactor chambers, gas inlets/outlets, heating elements, fixtures, and enclosures Ensures mechanical integrity and thermal tolerance
Electrical/Electronic Engineer	Develops control systems, sensors, heating control, and safety interlocks Handles wiring, PCB design (if needed), and system integration
Automation / Control Engineer	Designs software and hardware for process automation Integrates sensors, feedback loops, and user interfaces
Nanomaterials Scientist / Chemist	Defines catalyst compositions, filter and substrate materials Analyzes the quality, structure, and yield of CNTs
Thermal design Engineer	Designs thermal management systems such as heaters, insulation, and cooling Models heat transfer and temperature gradients inside the reactor
Simulation/Modeling Engineer	Simulates fluid dynamics (CFD), heat distribution, and gas flow Optimizes system design through digital twins or modeling software
Systems Architect	Defines the overall structure of the CNT synthesis system, integrating mechanical, electrical, and control subsystems Aligns design across domains to meet performance, scalability, and modularity requirements Ensures system coherence, interfaces, and future extensibility across R&D, manufacturing, and field deployment

Table 9. Supporting Roles

Role	Job description
Manufacturing Engineer	Translates designs into manufacturable solutions Oversees fabrication, machining, welding, and assembly processes
Quality Assurance / Test Engineer	Defines test procedures and acceptance criteria for systems and CNT outputs Verifies compliance with quality standards and safety norms
Project Manager	Coordinates timelines, resources, and communication between teams Tracks milestones and manages budgets
Compliance and Safety Engineer	Ensures the system complies with environmental, health, and safety regulations such as gas handling, high temperatures, and nanomaterial risks
Data Scientist / Analyst	Analyzes data from sensors and CNT output characterization Optimizes process parameters through statistical or AI-driven analysis
Procurement Agent	Places purchase orders and follows up delivery of components

After specifying the role descriptions, the list of activities, and their related agents are defined using RACI matrix presented in Table 10.

Table 10. RACI Matrix

Activity ID	Activity	Marketing Manager	Application Engineer	Process Engineer	Mechanical Design Engineer	Electrical / Electronic Engineer	Automation / Control Engineer	Nanomaterials Scientist / Chemist	Thermal design Engineer	Simulation / Modeling Engineer	Systems Architect	Manufacturing Engineer	Quality Assurance / Test Engineer	Project Manager	Systems R&D Leader	Compliance / Safety Engineer	Field Service Engineer	Procurement Agent
A1	Define initial application requirements	A	R								R			I	C			
A2	Perform feasibility and risk assessment	C	C	R							R			I	A	C		
A3	Refine and parameterize requirements		C	R	C	C	C	C	C		R			I	A	C		
A4	Develop system architecture		C	C	C	C	C	C	C		R			I	A	C		
A5	Review architecture and requirements			C	I	I	I				R			I	A	C		
A6	Select synthesis process and flow parameters		C	R				C			C			I	A			
A7	Select catalyst, filter and substrates		C	C				R						I	A			
A8	Review synthesis process and catalyst selection			C				C			R			I	A			
A9	Design reactor hardware, thermal solution, and gas delivery system			C	R				R		C			A	I	C		
A10	Simulate reactor flow and heat distribution			C	C			C	C	R	A			I	I	I		
A11	Review reactor and thermal design and simulation results		I		C				C	C	R			I	A	C		
A12	Design control system and automation			C	C	R	R				A			I	I			
A13	Review control and automation			C	C	C	C				R			A	I	C		
A14	Manufacture and supply subsystems										C	R		A	I			R
A15	Test subsystem prototypes		C	C							C		R	A	I			
A16	Review subsystem tests results		C		C		C				R		C	I	A			
A17	Assemble integrated CNT system		C		C						C	R		A	I	C		
A18	Test integrated system as factory acceptance test		C								A		R	I	I	C		
A19	Review integrated system performance and FAT results		C								R		C	I	A	C		
A20	Standardize subsystems as qualified modules		C								R		C	I	A	C	C	
A21	Freeze and approve design	I									C			R	A			
A22	Install and ramp-up production	I	C									R	C	A	I	C	R	
A23	Collect field performance feedback	I	I	I							I	I	I	I	I	I	R	
A24	Final Review										R		C	I	A	C		
A25	Project close documentation	I									I			A	I		C	

Subsequently, tables containing all systems design activities, their input and output data, and the link between the data is drafted based on Workflow Matrix that introduced in section 4.1 to structure the improved workflow. These tables, in addition to the performed WFM steps, are annexed in Appendix 2.

After structuring the activities sequence and finding the iteration loops using WFM, a flowchart is drafted to present the resulting improved systems design workflow as shown in Figure 3.

This improved workflow has several reviewing steps with targeted feedback loops to ensure the integrity of the resulting system, avoid transferring possible flaws to the following steps, and decrease the amount of reworking. These reviews also preserve the flexibility and adaptability of the workflow and improve collaboration between the stakeholders involved. The review steps can be considered as the starting point of existing equipment modification process and fulfill the idea of separating new system design and upgrading current systems processes.

It also has clear initial steps for specifying the parametrized system requirements and risk assessment with specified responsible agents which simplifies the initial decision-making process.

Additionally, it includes a step for standardizing the qualified sub-systems to be used in multiple future products and pave the road towards platform-based design.

The documented review results are also included in the workflow which enables generating a retrievable archive for design change rationale and using Six W’s Model as introduced in Section 4.3.

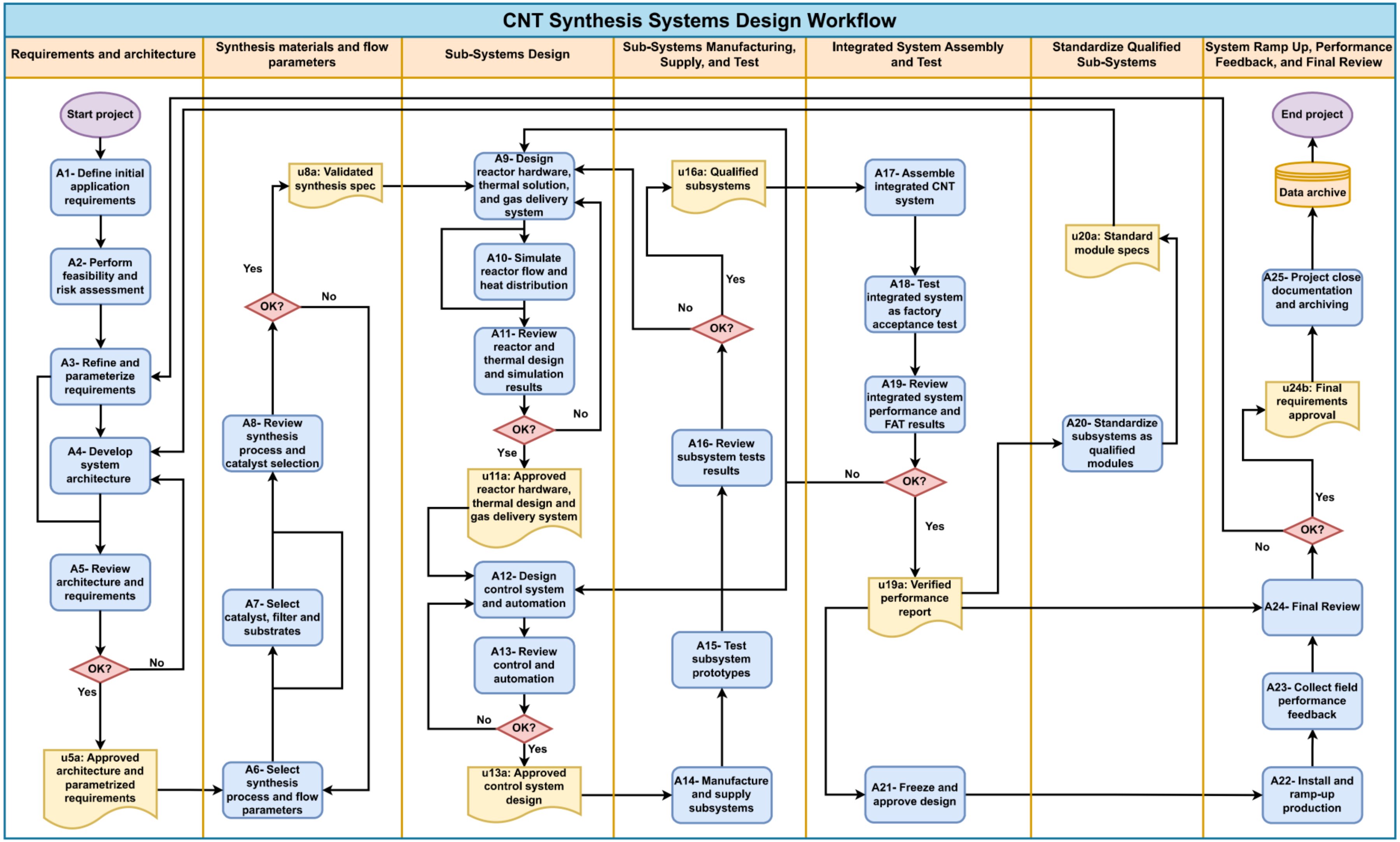

Figure 3. Initial improved systems design workflow

It can be seen in Figure 3 that the improved workflow is divided into the main systems design stages including requirements and architecture, synthesis materials and flow parameters, sub-systems design, sub-systems manufacturing, supply, and test, integrated system assembly and test, standardize qualified sub-systems, and system ramp up, performance feedback, and final review. The activities in each stage are closely related and performed within a team to speed up communication and improve collaboration.

In the next chapter, the feedback validation of the initial improved workflow is described and the final proposal for an improved systems design workflow is presented.

6 Feedback Validation of Proposed Systems Design Workflow

The initial improved workflow presented in the previous chapter. In this chapter, the feedback validation process of the initial improved workflow including the data collection stage, summary of received feedback and suggestions, and the final improved systems design workflow is presented.

6.1 Overview of Data 3 Collection

Data 3 collection stage was performed as an in-person workshop at the case company. The participants of the workshop included the CEO of the case company, VP of Manufacturing Equipment, Head of Systems Engineering, and Head of CAD/CAE.

The CEO was not involved in stages 1 and 2 of data collection. The reason for including him in the final stage is that he could offer a unique and high-level perspective that can validate and refine the findings of the study. His feedback helps to ensure that the research conclusions are aligned with the strategic priorities and real challenges of the company and increase both the practical value and the academic rigor of the outcome.

During the workshop, the initial improved systems design workflow was presented and feedback and suggestions for further refinement of the workflow were received from the participants. The workshop was documented as a recorded and transcribed video. The content of the workshop was reviewed and the key points mentioned by the participants were extracted as described in the following section.

6.2 Feedback Received and Corrections to Initial Workflow

The participants in the feedback validation workshop provided very positive comments and feedback regarding different aspects of the initial proposed workflow. Overall, it was evaluated as valid, relevant, and ready to be implemented gradually with minor refinement.

The summary of feedback and comments received from the participants are as follows:

> *Clear roles and responsibilities help, because everyone knows what to do… What I can expect from you and what you can expect from me. So, RACI model and how you use it makes perfect sense… Platforms are great advantages from the perspective that you don't need to do the same design work twice… yes, we are losing some flexibility there, but it is way more cost-efficient way to design… Thinking about longer term, we can define clear interfaces and create modules like reactor area, pipe area, chamber area… It needs someone as system architect, that you have defined in the roles, who decides how different modules communicate… For requirement identification it is important to have iteration loops, as you have proposed, because seldom do people know requirements straight away… It is important that you do iteration as early as possible… Overall, I see this proposal quite relevant to our needs… (CEO)*

> *This proposal is a very good base information for our ISO 9001 review to see how we are doing the designs as we should have the processes existing for the audit… I really like this academic approach to going to the leaders and having interviews with multiple different departments… and the highlights that you have about strengths and weaknesses are the common issues felt by people in the company… For requirements, a very solid next step is preparing a template that has the requirement identifiers and descriptions and shows from where or which owner the requirements are coming from… The roles and responsibilities as you have defined, addresses inbuilt weak point of the company, as the ownership of products are currently defined mostly within core engineering while it needs to be*

owned by product manager or R&D manager… this proposal looks already very good, but in next steps we can further develop and strengthen it to include as upstream activities as possible, for example, having separate workflow for installed based product instances which is excluded from this thesis, to get it then step-by-step implemented... (VP of Manufacturing Equipment)

The scientific approach in your work is quite impressive. So, kudos for that! In general, the workflow steps and roles and responsibilities go hand in hand as you have them in RACI matrix… I think that's a good point, to have roles and responsibilities separately defined as you have, while in reality at the moment they might be merged and assigned to one person… Regarding the sequence of activities in the proposal I think it needs to be rearranged in initial steps to select synthesis specs before developing system architecture because that is the way we proceed in reality… I also think gradual implementation of this proposal is very important because if you try to change everything at once, it faces exponentially more resistance to the change… (Head of CAD/CAE)

Overall, I see the weaknesses that were identified are addressed in your proposal… RACI matrix needs a bit of revision in my view specially for risk assessment most stakeholder can be responsible or consulted… the workflow is clear in general; however, I think the final review step need to be rethought and maybe some refinement is needed in final stages of the workflow… the move towards platform-based design is quite necessary and actually we have started it with SEMI2.0 project… (Head of Systems Engineering)

As mentioned in the above quotes, there are a few suggestions for correcting the workflow proposal. Head of CAD/CAE suggested rearranging the initial steps of the workflow and selecting synthesis specs before system architecture development. Also, Head of Systems Engineering suggested refining the Final Review step in the workflow to be clearer and more descriptive in addition to revising the RACI matrix for the risk assessment activity to assign the role for all the relevant stakeholders.

6.3 Summary of Final Proposal of an Improved Systems Design Workflow

The RACI matrix updated to include relevant consulted stakeholders in the risk assessment activity as suggested by Head of Systems Engineering and the updated activity list. The updated RACI matrix with changed parts highlighted is shown in Table 11.

Table 11. Updated RACI Matrix

Activity ID	Activity	Marketing Manager	Application Engineer	Process Engineer	Mechanical Design Engineer	Electrical / Electronic Engineer	Automation / Control Engineer	Nanomaterials Scientist / Chemist	Thermal design Engineer	Simulation / Modeling Engineer	Systems Architect	Manufacturing Engineer	Quality Assurance / Test Engineer	Project Manager	Systems R&D Leader	Compliance / Safety Engineer	Field Service Engineer	Procurement Agent
A1	Define initial application requirements	A	R								R			I	C			
A2	Perform feasibility and risk assessment	C	C	R	C	C	C	C	C	C	R	C	C	I	A	C		
A3	Refine and parameterize requirements		C	R	C	C	C	C	C		R			I	A	C		
A4	Develop system architecture		C	C	C	C	C	C	C		R			I	A	C		
A5	Review architecture and requirements			C	I	I	I				R			I	A	C		
A6	Select synthesis process and flow parameters		C	R				C			C			I	A			
A7	Select catalyst, filter and substrates		C	C				R						I	A			
A8	Review synthesis process and catalyst selection			C				C			R			I	A			
A9	Design reactor hardware, thermal solution, and gas delivery system			C	R				R		C			A	I	C		
A10	Simulate reactor flow and heat distribution			C	C			C	C	R	A			I	I	I		
A11	Review reactor and thermal design and simulation results		I		C				C	C	R			I	A	C		
A12	Design control system and automation			C	C	R	R				A			I	I			
A13	Review control and automation			C	C	C	C				R			A	I	C		
A14	Manufacture and supply subsystems										C	R		A	I			R
A15	Test subsystem prototypes		C	C							C		R	A	I			
A16	Review subsystem tests results		C		C		C				R		C	I	A			
A17	Assemble integrated CNT system		C		C						C	R		A	I	C		
A18	Test integrated system as factory acceptance test		C								A		R	I	I	C		
A19	Review integrated system performance and FAT results		C								R		C	I	A	C		
A20	Standardize subsystems as qualified modules		C								R		C	I	A	C	C	
A21	Freeze and approve design	I									C			R	A			
A22	Install and ramp-up production	I	C									R	C	A	I	C	R	
A23	Collect field performance feedback	I	I	I							I	I	I	I	I	I	R	
A24	Detailed system review										R		C	I	A	C		
A25	Project close documentation	I									I			A	I		C	

Also, the initial workflow proposal is modified based on the suggestions received from Head of CAD/CAE and Head of Systems Engineering. The final improved systems design workflow is presented in Figure 4.

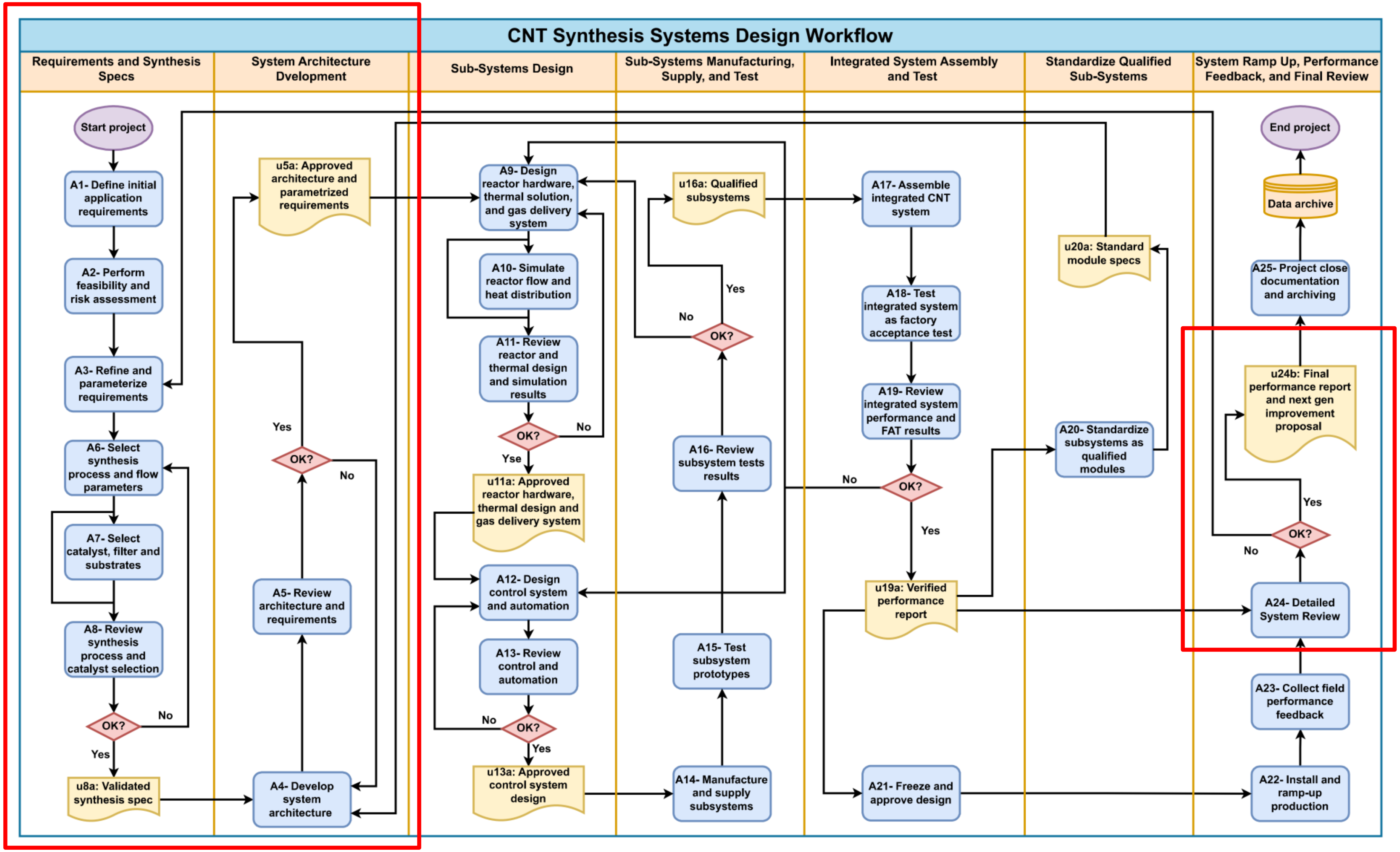

Figure 4. Final improved systems design workflow

The red rectangles in Figure 4 illustrate the modified parts of the workflow compared to the initial proposal. The sequence of activities in the first two stages are rearranged to fulfill the priority of selecting synthesis specs. Also, the “Detailed System Review” has replaced the previous “Final Review” activity to clarify its purpose.

The next chapter summarizes the steps carried out in the thesis and describes the next steps to be performed for implementation of the proposed workflow. Also, it includes the self-evaluation of the study by the author.

7 Discussion and Conclusion

In this final chapter, an executive summary of the steps carried out in the thesis, practical next steps for implementation of the proposed workflow, and a self-evaluation of the study process are presented. The study is concluded with a few closing words.

7.1 Executive Summary

The case company of this study leads in developing advanced Carbon Nanotubes (CNTs) and reactors for applications such as semiconductors, automotive, and medical diagnostics. The company needs to develop the CNT synthesis equipment continuously and requires better systems design workflow. Its legacy practice has been based on project definition instead of a product-centered approach. Their current approach suffers from inconsistency, and unclear decision-making processes which are costly and use the resources inefficiently. The objective of this study was to improve the systems design workflow for developing CNT production equipment at the case company. The outcome of the study was a proposal for an improved systems design workflow in the case company.

The methodology of this study was selected to be based on Applied Action Research since the issue was about a specific company where immediate practical solutions were targeted. The study was planned to be carried out in four practical stages. In the first stage, a current state analysis was performed to identify the strengths and weaknesses of the existing design process and create a map of the current workflow. In the second stage an extensive literature review was carried out to collect ideas and approaches for improving the identified weaknesses and structuring a conceptual framework accordingly. In the third stage, the conceptual framework was analyzed and discussed together with the stakeholders at the case company to co-create ideas for the initial improved workflow proposal and then the initial proposal was drafted. In the last stage, the initial proposal was presented in a workshop and validated through feedback from selected stakeholders and the CEO of the company. At the end, the feedback and comments from the workshop participants were used to draft the final improved systems design workflow.

The above-mentioned stages required three rounds of data collection involving informants with roles and expertise related to the systems design activities at the case company. The data collection method included two structured and documented online interviews and one in-person workshop at the case company. The selected informants consisted of VP Manufacturing Equipment, Head of Systems Engineering, Head of CAD/CAE, CNT Technology Core Engineer, Sr. EIA Project Manager, Mechanical and Development Engineers, and the CEO of the company. In addition, a few field notes were recorded by the author as a Sr. Mechanical Engineer who is closely involved in the design processes.

The current state analysis revealed that there are noticeable strengths in the current systems design workflow such as Team Resilience, Adaptability, Fast Design Cycles, Emerging Improvements, and Collaborative Effort. However, there were weaknesses in the design workflow that needed to be addressed. The weaknesses were in two categories comprising design data flow management issues and practical and behavioral issues. In this study, the focus was on finding solutions for improving the design data flow management issues especially on Vague or Incomplete Requirements, Unclear Roles and Responsibilities, Inconsistent or Missing Reviews, Lack of a Formal Design Process, Unstructured Change Requests, and Ownership and Oversight Issues. The literature review

The initial improved workflow was created using the workflow structuring method called Workflow Matrix and based on the co-created ideas from literature and interviews. Required roles and responsibilities were clarified with the task description and the activities for each step of the design process were defined with special attention to the identified weaknesses of the current workflow. The input and output data of each activity were defined and the link between them were sorted. The result was presented in the form of a flowchart to show the design stages and the activities sequence in addition to the iteration loops.

The validation of the initial improved systems design workflow was carried out through feedback workshop where the CEO of the company, VP Manufacturing Equipment, Head of Systems Engineering, and Head of CAD/CAE were present. Most of the proposed solutions such as overall structured workflow, defined roles and responsibilities, moving towards platform-based design, and structured requirement identification steps received positive and confirming feedback from the participants. Also, a few refinements were suggested including rearranging two initial stages of the workflow, clarifying the final review activity, and updating the RACI matrix for risk assessment activity.

To conclude the outcome of this study, the suggested refinements were applied to the initial proposal and the final improved systems design workflow for the case company was drafted and presented. The updated RACI matrix was also presented as part of the final proposal.

7.2 Practical Next Step Recommendations

The outcome of this study is a proposal for an improved systems design workflow for the case company which needs to be implemented and evaluated in practice. This can be achieved by further developing the workflow to include the installed based product instances and gradual implementation. During the feedback validation workshop the proposal was also considered a good basis for preparing the required documentation for the upcoming ISO 9001 audit. In addition, for practicality of the system requirements identification, requirements templates with identifiers, and descriptions showing the roots and the owners of the requirements must be drafted. Moreover, defining detailed steps and metrics for sub-systems validation and productization to facilitate the move towards platform-based design is necessary. Additionally, a digital platform for tracking decisions, and logging and retrieving design change rationale based on the review steps reports is required to be established.

7.3 Self-evaluation of the Study

This study used the Applied Action Research method, which was well suited for the topic. Since the objective was to solve a real problem in a specific company and to create practical results, this approach allowed close collaboration with the stakeholders at the case company and supported a hands-on approach throughout the project.

The validity of the study was supported by its structured design. It was carried out in four clear stages, and the plan was followed carefully. Each stage built on the previous one, making the process logical and structured. This helped to ensure that the results were based on actual problems and real feedback from people working in the company.

The credibility and reliability of the study were supported by collecting data from different departments involved in systems design. The informants had key roles such as VP Manufacturing Equipment, Head of Systems Engineering, and others closely involved in the design process. The interviews were recorded, transcribed, and directly quoted in the report, which adds to the credibility and transparency of the research. Also, field notes taken by the author as a Sr. Mechanical Engineer who is closely involved in the design process added further insight and context to the outcome.

The literature review focused on peer-reviewed and solution-based sources, helping to build a solid conceptual framework for improving the workflow. The ideas from the literature were then combined with ideas from the interviewees to create the initial improved workflow. This made the proposed improved workflow both relevant and practical for the case company.

The objective of the study - to improve the systems design workflow - was fully achieved. The initial proposal was feedback validated in a workshop where key stakeholders, including the CEO, participated and provided feedback. Most parts of the proposal were well received, and a few small changes were suggested that were included in the final version.

One limitation was the time available for interviews. With extra time and an increased number of participants, the workflow could have been made even more detailed and accurate. Still, the result is a strong and useful proposal that fits the company’s current needs and gives a reliable basis for future improvements.

7.4 Conclusion

In conclusion, the study was well planned, carefully carried out, and was based on credible information and input from real experts. The final workflow is reliable, relevant, and ready to be used as a starting point for further development at the case company. The workflow structuring method used in this study, or the Workflow Matrix (WFM) can be utilized in all other companies that are focused on systems design or product development to improve their design workflow.

References

Collimator, 2022. The Ultimate Engineering Guide to System Design in Hardware & Software [WWW Document]. URL https://www.collimator.ai/post/what-is-system-design (accessed 12.3.24).

Ferrari, A., Sangiovanni-Vincentelli, A., 1999. System design: Traditional concepts and new paradigms. Proceedings - IEEE International Conference on Computer Design: VLSI in Computers and Processors 2–12. https://doi.org/10.1109/ICCD.1999.808256

GräBler, I., Thiele, H., Grewe, B., Hieb, M., 2022. Responsibility Assignment in Systems Engineering. Proceedings of the Design Society 2, 1875–1884. https://doi.org/10.1017/PDS.2022.190

Hedrick, T.E.., Bickman, Leonard., Rog, D.J.., 1993. Applied Research Design A Practical Guide.

Heejung, L., Hyo Won, S., 2006. Workflow structuring and reengineering method for design process. Comput Ind Eng 51, 698–714. https://doi.org/10.1016/J.CIE.2006.08.016

Heller, M., Jäger, D., Schlüter, M., Schneider, R., Westfechtel, B., 2004. A management system for dynamic and interorganizational design processes in chemical engineering. Comput Chem Eng 29, 93–111. https://doi.org/10.1016/J.COMPCHEMENG.2004.07.025

Kananen, J., 2013. Design research (applied action research) as thesis research: A practical guide for thesis research. Jyväskylä University of Applied Sciences.

Kothari, C.R.., 2004. Research methodology : methods & techniques 401.

Production equipment department of the case company, 2025. Equipment development and equipment production processes draft.

Roucoules, L., Yahia, E., Es Soufi, W., Tichkiewitch, S., 2016. Engineering design memory for design rationale and change management toward innovation. CIRP Annals 65, 193–196. https://doi.org/10.1016/J.CIRP.2016.04.046

Rouibah, K., Caskey, K., 2003. A workflow system for the management of inter-company collaborative engineering processes. Journal of Engineering Design 14, 273–293. https://doi.org/10.1080/0954482031000091059

Saunders, M., Lewis, P., Thornhill, A., 2023. Research methods for business students (9th ed.). Pearson. 860.

WFMC, 1999. Workflow Management Coalition Terminology & Glossary. Workflow Management Coalition.

Current State Analysis Structured Interview Questions

1. Can you describe the overall systems design workflow, from start to finish, for a project? What are the key stages or milestones?
2. Who are the main stakeholders involved in the systems design workflow, and what are their roles? (Examples: mechanical engineers, electrical engineers, project managers, external suppliers)
3. What tools, software, or methodologies are used in the workflow? (Examples: CAD, simulation tools, project management software)
4. What aspects of the current workflow work particularly well? Why? (Examples: collaboration, documentation, use of tools)
5. Are there any specific steps or processes that consistently lead to successful outcomes? Can you share examples?
6. How do you ensure the workflow aligns with project timelines and budgets?
7. What are the biggest challenges or pain points in the current workflow? (Examples: delays, communication issues, integration problems)
8. Are there any recurring issues during the requirements gathering phase, design or simulation phase, or prototyping and testing phase?
9. How often do you encounter design revisions or rework? What are the main causes?
10. Are there any processes that feel redundant or unnecessarily time-consuming?
11. What feedback have you received from clients or stakeholders about the design process?

12. Who else in the company should I speak to for additional insights into this process?

13. Could you sketch a quick workflow map or walk through the stages?

14. Is there anything else you'd like to share about the systems design workflow?

Table 12. Activity list

ID	Activity	Input Data	Output Data
A1	Define initial application requirements	_	u1a: Initial requirements spec based on market trend or customer request
A2	Perform feasibility and risk assessment	v2a: Initial requirements spec	u2a: Feasibility report u2b: Risk assessment
A3	Refine and parameterize requirements	v3a: Feasibility report v3c: Updated next gen requirement spec	u3a: Parameterized requirements
A4	Develop system architecture	v4a: Parameterized requirements v4b: Updated requirements v4c: Standard module specs	u4a: System architecture design
A5	Review architecture and requirements	v5a: System architecture design v5b: Parameterized requirements	u5a: Approved architecture and parametrized requirements u5b: Updated requirements
A6	Select synthesis process and flow parameters	v6a: Approved architecture and parametrized requirements v6b: Synthesis spec update request	u6a: Process parameters spec
A7	Select catalyst, filter and substrates	v7a: Process parameters spec	u7a: Materials specification
A8	Review synthesis process and catalyst selection	v8a: Process parameters spec v8b: Materials specification	u8a: Validated synthesis specs u8b: Synthesis spec update request
A9	Design reactor hardware, thermal solution, and gas delivery system	v9a: Validated synthesis specs v9b: Hardware design change request v9c: FAT change request V9d: Subsystem change request	u9a: Reactor mechanical and thermal design, collection piping
A10	Simulate reactor flow and heat distribution	v10a: Reactor mechanical and thermal design, collection piping	u10a: Simulation results
A11	Review reactor and thermal design and simulation results	v11a: Reactor mechanical and thermal design, collection piping v11b: Simulation results	u11a: Approved reactor hardware, thermal design and gas delivery system u11b: Hardware design change request
A12	Design control system and automation	v12a: Approved reactor hardware, thermal design and gas delivery system v12b: Control design change request v12c: FAT change request	u12a: Control and automation design
A13	Review control and automation	v13a: Control and automation design	u13a: Approved control system design u13b: Control design change request
A14	Manufacture and supply subsystems	v14a: Approved control system design v14b: Approved reactor hardware, thermal design and gas delivery system	u14a: Manufactured subsystems
A15	Test subsystem prototypes	v15a: Manufactured subsystems	u15a: Subsystem test results
A16	Review subsystem tests results	v16a: Subsystem test results	u16a: Qualified subsystems u16b: Subsystem change request
A17	Assemble integrated CNT system	v17a: Qualified subsystems	u17a: Assembled CNT system
A18	Test integrated system as factory acceptance test	v18a: Assembled CNT system	u18a: FAT results
A19	Review integrated system performance and FAT results	v19a: FAT results	u19a: Verified performance report u19b: FAT change request
A20	Standardize subsystems as qualified modules	v20a: Verified performance report	u20a: Standard module specs
A21	Freeze and approve design	v21a: Verified performance report	u21a: Final design package
A22	Install and ramp-up production	v22a: Final design package	u22a: Operational system
A23	Collect field performance feedback	v23a: Operational system	u23a: Field feedback report
A24	Final Review	v24a: Field feedback report v24b: Verified performance report	u24a: Updated next gen requirement spec u24b: Final requirements approval
A25	Project close documentation and archiving	v25a: Final requirements approval review and archive	_

Table 13. Data link table for Workflow Matrix

Data Link	From Activity	To Activity	Sensitivity (0–3)	Criticality (0–2)	Routing type
(u1a, v2a)	A1	A2	3	2	S
(u10a, v11b)	A10	A11	2	1	A
(u11a, v12a)	A11	A12	3	0	O
(u11a, v14b)	A11	A14	3	0	O
(u11b, v9b)	A11	A9	2	0	O
(u12a, v13a)	A12	A13	3	2	S
(u13b, v12b)	A13	A12	2	0	O
(u13a, v14a)	A13	A14	3	0	O
(u14a, v15a)	A14	A15	3	2	S
(u15a, v16a)	A15	A16	2	2	S
(u16a, v17a)	A16	A17	2	0	O
(u16b, v9d)	A16	A9	1	0	O
(u17a, v18a)	A17	A18	2	2	S
(u18a, v19a)	A18	A19	2	2	S
(u19b, v12c	A19	A12	1	0	O
(u19a, v20a)	A19	A20	2	0	O
(u19a, v21a)	A19	A21	3	0	O
(u19a, v24b)	A19	A24	2	1	A
(u19b, v9c)	A19	A9	1	0	O
(u2a, v3a)	A2	A3	2	2	S
(u20a, v4c)	A20	A4	1	0	O
(u21a, v22a)	A21	A22	3	2	S
(u22a, v23a)	A22	A23	2	2	S
(u23a, v24a)	A23	A24	1	1	A
(u24b, v25a)	A24	A25	3	0	O
(u24a, v3c)	A24	A3	1	0	O
(u3a, v4a)	A3	A4	2	2	S
(u3a, v5b)	A3	A5	2	1	A
(u4a, v5a)	A4	A5	3	1	A
(u5b, v4b)	A5	A4	2	0	O
(u5a, v6a)	A5	A6	2	0	O
(u6a, v7a)	A6	A7	3	2	S
(u6a, v8a)	A6	A8	3	1	A
(u7a, v8b)	A7	A8	3	1	A
(u8b, v6b)	A8	A6	2	0	O
(u8a, v9a)	A8	A9	3	0	O
(u9a, v10a)	A9	A10	3	1	A
(u9a, v11a)	A9	A11	3	1	A

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25
A1																									
A2	S																								
A3		S																						O	
A4			A		O															O					
A5			A	A																					
A6					S			O																	
A7						A																			
A8						A	S																		
A9								O			O					O			O						
A10									A																
A11									A	A															
A12											O		O						O						
A13												S													
A14											O		O												
A15														S											
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A21																			O						
A22																					S				
A23																						S			
A24																			A				A		
A25																								O	

Figure 5. Initial ill-structured Workflow Matrix

	A1	A2	A3	A4, A5	A6, A7, A8	A9, A10, A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25
~~A1~~																				
~~A2~~	S																			
~~A3~~		S																		
~~A4, A5~~			A																	
~~A6, A7, A8~~																				
A9, A10, A11											O			O						
A12						O		O						O						
A13							S													
A14						O		O												
A15									S											
A16										S										
A17											O									
A18												S								
A19													S							
~~A20~~														O						
~~A21~~														O						
~~A22~~																S				
~~A23~~																	S			
~~A24~~														A				A		
~~A25~~																			O	

Figure 6. Well-structured Workflow Matrix

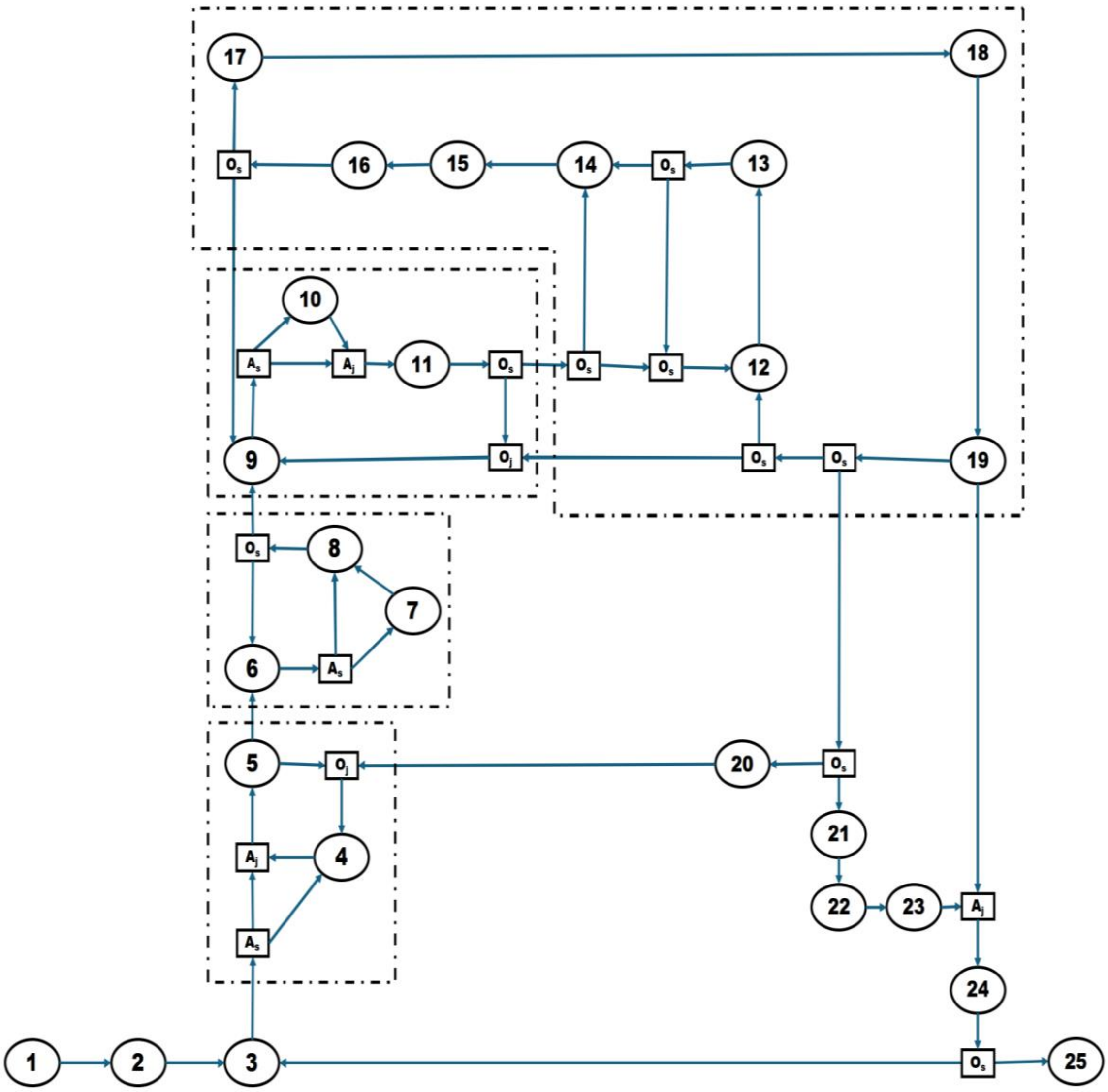

Figure 7. Network representation of well-structured Workflow Matrix