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COMPREHENSIVE SYSTEM MODELING OF A MICRO-REFORMER FOR SYNGAS PRODUCTION USING MBSE PRINCIPLES WITHIN THE CAPELLA/ARCADIA FRAMEWORK

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Work presented as a requirement for obtaining the title of Bacharel em Aerospace Engineering, in the Technological Center of Joinville, of the Federal University of Santa Catarina.

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This Course Conclusion Paper has been judged suitable for obtaining the degree of Bacharel em Aerospace Engineering, in the Technological Center of Joinville, of the Federal University of Santa Catarina.

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I dedicate this work to my parents, Adnelson and Denise, that much helped to make of me who I am.

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ABSTRACT

This study presents the design and modeling of a micro-reformer for SynGas production using Model-Based Systems Engineering (MBSE) principles within the Capella - ARCADIA framework. The main objective was to create a comprehensive system model capturing the operational, functional, and physical architectures of the reformer, ensuring that each stage of design aligned with stakeholder requirements and performance goals. The research began with Operational Analysis to identify stakeholder needs and define system boundaries, forming a high-level understanding of essential interactions. This foundation guided the System Analysis phase, where system functionalities and expected behaviors were articulated, detailing how the reformer should interact with external elements. Logical Architecture further refined the design by decomposing the system into abstract components with defined interaction principles, maintaining flexibility in implementation. In the final Physical Architecture phase, these abstract elements were translated into concrete, implementable components, laying out the structural design ready for potential construction. Results demonstrate that MBSE, applied through Capella, provides a structured approach to complex system design, promoting consistent requirements management and enabling iterative validation at each design phase. Challenges such as coordinating interdisciplinary inputs and maintaining model coherence across phases were effectively managed through Capella's structured methodology, underscoring the reliability and adaptability of MBSE in complex energy system projects.

Palavra-chave: Model Based Systems Engineering. MBSE. SynGas. Compact Reactor.

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1 INTRODUCTION

The global energy landscape faces a challenge: conciliate the growing demand for energy with the scarcity of fossil fuels and the intensification of climate change. In this context, the search for new alternative e renewable energy sources becomes ever more urgent. Hydrogen appears as one of the most promising fuels for the future, that is due to its high energetic density, clean combustion and the possibility of producing it from green sources such as solar and wind power (CHANGE, 2022). In the aerospace sector, hydrogen has shown significant potential in decarbonizing aviation, drastically reducing the greenhouse effect gas emission and the environmental impact of the industry (AIRBUS, 2022). The use of hydrogen in aircraft can bring many benefits, such as lower noise and air pollution (BOEING, 2021).

As of 2022, global hydrogen production reached the mark of 95 Mt, but its overwhelming majority was produced using fossil fuels: In 2021 natural gas without carbon capture, utilization and storage (CCUS) was used in 62% of all output, unabated coal for 21% and hydrogen produced as a by-product of petrochemical reforming for another 16%. Low-emission hydrogen production accounts for a mere 0,7% of total global offering (AGENCY, 2021). The method and raw material used to produce hydrogen can be used to classify it according to the impact on the environment: low-emission H_2 production methods encompass green hydrogen (produced from renewable sources) and blue hydrogen (produced from fossil fuels with carbon capture techniques), while high-emission H_2 is classified as grey hydrogen (EMETERE et al., 2024).

To enable the large-scale production of low-emission, environmentally friendly green hydrogen, the development of efficient and sustainable technologies is crucial. Alternative energy sources such as wind, solar, nuclear, hydropower, geothermal and biogas have a significant importance in the current outlook for future green hydrogen production (ZHANG et al., 2016). Natural Gas (NG) is currently the most financially competitive source for Hydrogen production and it is mainly comprised of methane. Biogas appears as a clean alternative to NG, for it is comprised of 45-75% of methane (CH_4), 20-55% carbon dioxide (CO_2), 5-10% hydrogen sulfide (H_2S), trace amounts of water vapor, hydrogen, nitrogen and other gases and is commonly considered a clean and renewable energy source (EMETERE et al., 2024).

One of the possible intermediaries in the production of hydrogen from biogas is SynGas (meaning Synthesis Gas), a mixture of around 85% CO and H_2, with small amounts of CO_2, nitrogen, and methane (TOLEDO et al., 2023). This mixture can be further refined to obtain pure hydrogen or other chemicals such as methanol, ethanol, gasoline, diesel, jet fuel, dimethyl ether, etc (GANGADHARAN et al., 2012). Processes to convert biogas into SynGas include dry-reforming, bi-reforming, tri-reforming, autothermal, partial oxidation and steam reforming. Bi-reforming is a particularly compelling method because it combines CO_2 and steam reforming reactions, which reduces coke formation and improves hydrogen yield. This process effectively utilizes the CO_2 present in biogas, making it a more environmentally friendly approach by converting greenhouse gases into valuable synthesis gas while avoiding common issues like catalyst deactivation that can arise in other reforming methods (ZHAO et al., 2020).

Designing reactors for this kind of conversion is a fundamentally complex activity, that involves not only the chemical aspect of the reaction but also the physical construction of such apparatus and all the electronic-digital interfaces that may be necessary to collect useful data in a research setting. To approach this challenge, the use of an organized and well-established methodology can be very useful. The field of model-based systems engineering provides methodology options to create a robust and organized design, such as the IBM Telelogic Harmony-SE, INCOSE Object-Oriented Systems Engineering Methodology (OOSEM), IBM Rational Unified Process for Systems Engineering (RUP SE) for Model-Driven Systems Development (MDSD), Vitech Model-Based System Engineering (MBSE) Methodology, JPL State Analysis (SA), and Capella/ARCADIA (ESTEFAN et al., 2007) (MINACAPILLI et al., 2022).

The last of which has its birth in the sector of aerospace. Created by THALES, a French aerospace and defense company, the Analysis & Design Integrated Approach (ARCADIA) and its accompanying open-source software Capella were originally used to design space- and aircraft systems but are also applicable in other areas and have been gaining popularity recently (BATISTA; HAMMAMI, 2016). Due to its creation in the aerospace sector, it can be used for the development of safe, trustworthy and high-performance systems (AERONAUTICS; ADMINISTRATION, 2017). This methodology guarantees the consideration of all system aspects, from its very beginning to its final implementation, making sure that the final system meets all requirements established on its conception, all inside an open-source and relatively user fliendly plattform that is Capella. Therefore, it is a perfect candidate for use in the design of a reactor to reform biogas into SynGas while maintaining a cohesive structure that will avoid mistakes and overlooking of critical features during its conception.

In this dissertation, the structure is organized to systematically approach the modeling of a micro-reformer, strongly based on the plate-sandwich design of (ZHENG et al., 2020a), for SynGas production using Model-Based Systems Engineering (MBSE) and the Capella/ARCADIA methodology. The introduction presents the context, motivation, and objectives of the research. Following that, the theoretical foundation chapter explores key concepts such as SynGas production processes, reformer technologies, MBSE principles, and the Capella/ARCADIA framework. The methodology details how MBSE was applied in designing the micro-reformer and in the development and analysis of the system model. The results and discussion section presents the outcomes of the model, its performance, and a comparison with traditional approaches. Finally, the conclusion summarizes the work, highlights contributions to the field, and suggests future research directions.

The objective of this work is to design and model a micro-reformer for SynGas production by applying Model-Based Systems Engineering (MBSE) principles, utilizing the Capella/ARCADIA methodology. Specifically, this research aims to develop a comprehensive system model that captures the operational, functional, and physical architecture of the reformer, ensuring optimal performance and integration of its subsystems. Additionally, the thesis seeks to demonstrate the advantages of using MBSE in reducing the complexity of the reformer's design process, enhancing system efficiency, and aligning the design with requirements.

2 THEORETICAL FOUNDATION

2.1 MODEL-BASED SYSTEMS ENGINEERING

Model-Based Systems Engineering (MBSE) has its roots in the 1990s when system engineers began to realize the limitations of traditional, document-based approaches in managing increasingly complex systems. Early developments focused on creating visual modeling languages like UML (Unified Modeling Language), which was initially adopted in software engineering but later extended to systems engineering to improve the communication of system designs. First defined under this nomenclature by (WYMORE, 2018) in 1993, it had its formal concept defined by the International Council on Systems Engineering (INCOSE) as part of their Vision 2020 in 2007. This document laid the groundwork for MBSE to become a standard practice, highlighting its potential to streamline the design, validation, and verification processes through comprehensive system models (FRIEDENTHAL et al., 2007). Since then, MBSE methodologies, such as SysML (Systems Modeling Language) and tools like Capella, have been instrumental in modeling complex systems across industries like aerospace, automotive, and energy, ensuring better traceability, system consistency, and integration across engineering disciplines.

MBSE is a formalized approach that is part of the systems engineering field that utilizes models as the primary means of communication, design and validation throughout the system's design process. As defined by (MADNI; SIEVERS, 2018): "MBSE is a holistic, systems engineering approach centered on the evolving system model, which serves as the “sole source of truth” about the system. It comprises system specification, design, validation, and configuration management". Through the creation and use of more comprehensive models, MBSE allows a more integrated and efficient approach through the lifespan of a system, from its conception to its operation and maintenance(WYMORE, 2018).

This approach is based on the creation and use of extensive models that represent different aspects of a system, including its structure, function, behavior and requirements (WYMORE, 2018). These models can be static or dynamic and can be used for several activities through the life cycle of a system, such as:

- Definition of Requirements: Models can used to capture and document the requirements of the system clearly and concisely, facilitating the communication between interested parts and guaranteeing that all are on the same page (NIELSEN et al., 2015).
- Analysis and Project: Models can be used to analyze the system and identify possible flaws or design problems before physical implementation. This can help

to reduce costs and development times (MADNI; SIEVERS, 2018).

- Verification and Validation: The models can be used to verify if the system meets the requirements and functions according to expectations. This can be achieved through simulations, analysis and tests (WYMORE, 2018).
- Documentation: The models can be used to generate technical documentation of the system, including diagrams, schematics and manuals (NIELSEN et al., 2015).

The adoption of MBSE reduces development costs and time, for it can help to identify and correct design problems in an initial phase of the system's life cycle, which can reduce development times and costs (MADNI; SIEVERS, 2018). It also allows for better communication and collaboration among different teams working on a project by providing a common language to the interested parts (NIELSEN et al., 2015). Significant improvements in quality. Agility and flexibility can also be obtained, for this approach guarantees that the system meets its requirements and works according to the expected, which can in turn increase the overall quality of the system while allowing the systems to be easily modified and adapted to requisite changes. (WYMORE, 2018) (MADNI et al., 2019).

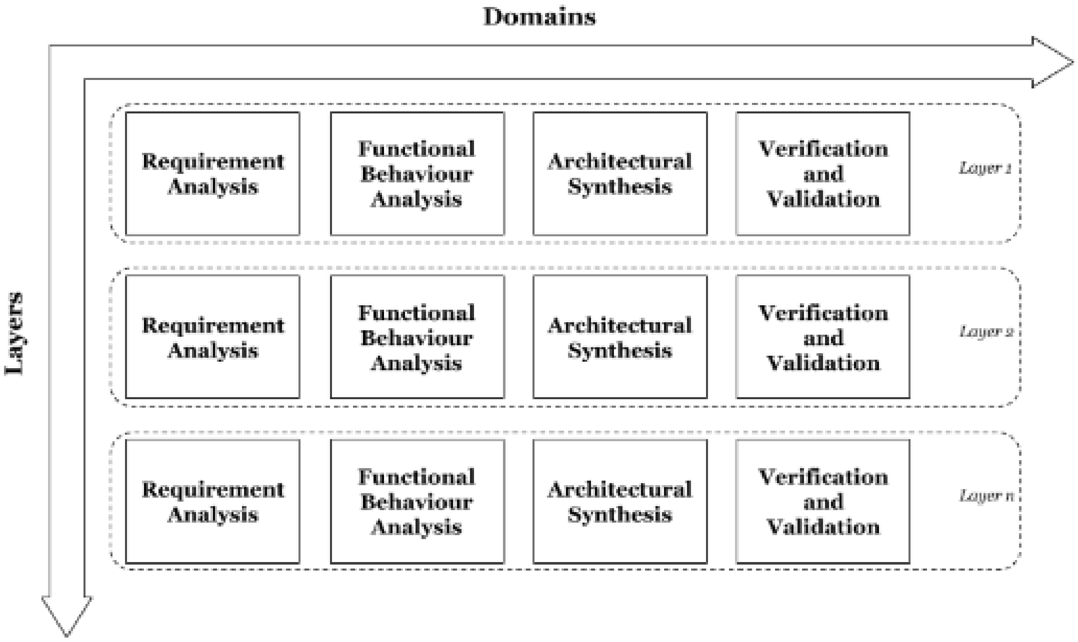
2.1.1 MBSE Formalism and Metodologies

In the past decade, an effort by the academic community, industry and councils such as INCOSE has taken place to create a formal base of knowledge and formalism for the field of MBSE. As described by (RAMOS et al., 2011), there are three important formalisms: The *semantic glossary and model for SE concepts* by (OLIVER et al., 2009), the *information model design* by (BAKER et al., 2000) and the *mathematical model for SE and MBSE* proposed by (WYMORE, 2018) in 1993. With the foundation composed of these documents, an unambiguous and robust base to work on MBSE can be achieved. According to (FRIEDENTHAL et al., 2014), a methodology can be defined as “a set of related activities, techniques, and conventions that implement one or more processes and is generally supported by a set of tools.” In the following paragraphs, the methodologies studied by (MAIO et al., 2021) will be presented.

2.1.1.1 Vitech MBSE Methodology

Named "STRATA" after its core idea of designing systems in layers, this methodology developed by *Vitech* has four core system engineering activities: *Source Requirements Analysis, Functional/Behavioural Analysis, Architecture/Systensis* and *Verification and Validation*. Those activities exist across the following domains: Requirements, Behavior, Architecture and Verification & Validation and support Top-Down, Bottom/Up and Middle-out approaches to system development. (MAIO et al., 2021) (ABOUSHAMA, 2020).

Figure 1 – STRATA domains



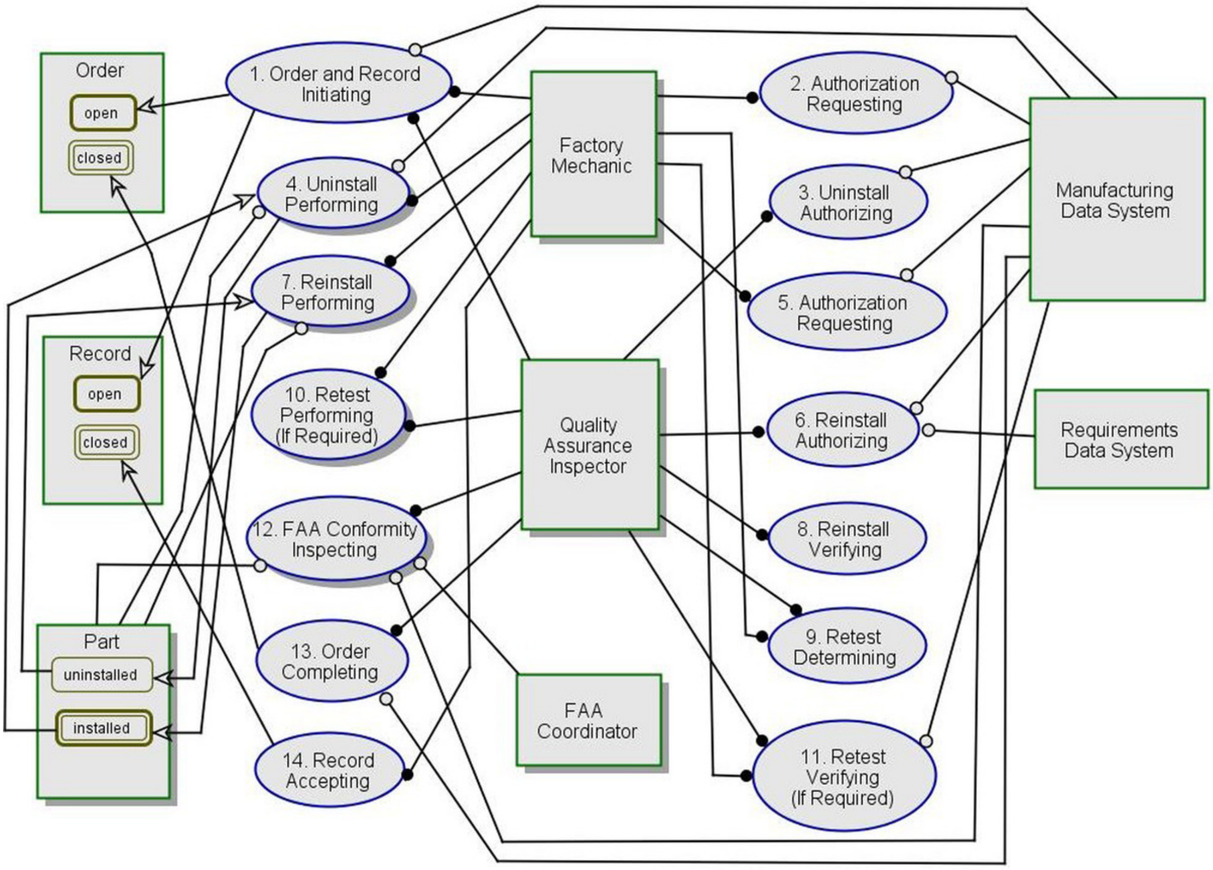
Source: (LONG; SCOTT, 2012)

STRATA uses the System Definition Language (SDL) to design and model its domains, this language attempts to enable understanding of the systems design process to stakeholders that might not be specialized, something that is not achievable with other common languages such as SysML. As for tools, users of this methodology have access to both *CORE*^{TM} and *GENESYS*^{TM}, which are respectively the first and second generation tools provided by Vitech (ABOUSHAMA, 2020).

2.1.1.2 Object-Process Methodology

Also designated by the acronym OPM, Object process methodology is a language defined by ISO/PAS 19450:2015 that can be compared to both SysML and UML. This conceptual modeling approach integrates both the structural and behavioral aspects of systems in a unified framework, every Object-Process Diagram (OPD) has a corresponding generated text in the Object-Porcess Language (OPL). This means that unlike other methodologies, that describe either static structures or dynamic models, OPM combines both while allowing such analysis to be presented graphically and textually, which in turn makes understanding by non-technically familiar members of the design team or possible clients easier. It is accompanied by the OPM online tool OPCloud has a very minimal user interface and allows users to call relations between different OPDs simply produced by them (MAIO et al., 2021) (CASEBOLT et al., 2020).

Figure 2 – Example of OPM layered architecture of Uninstalling process



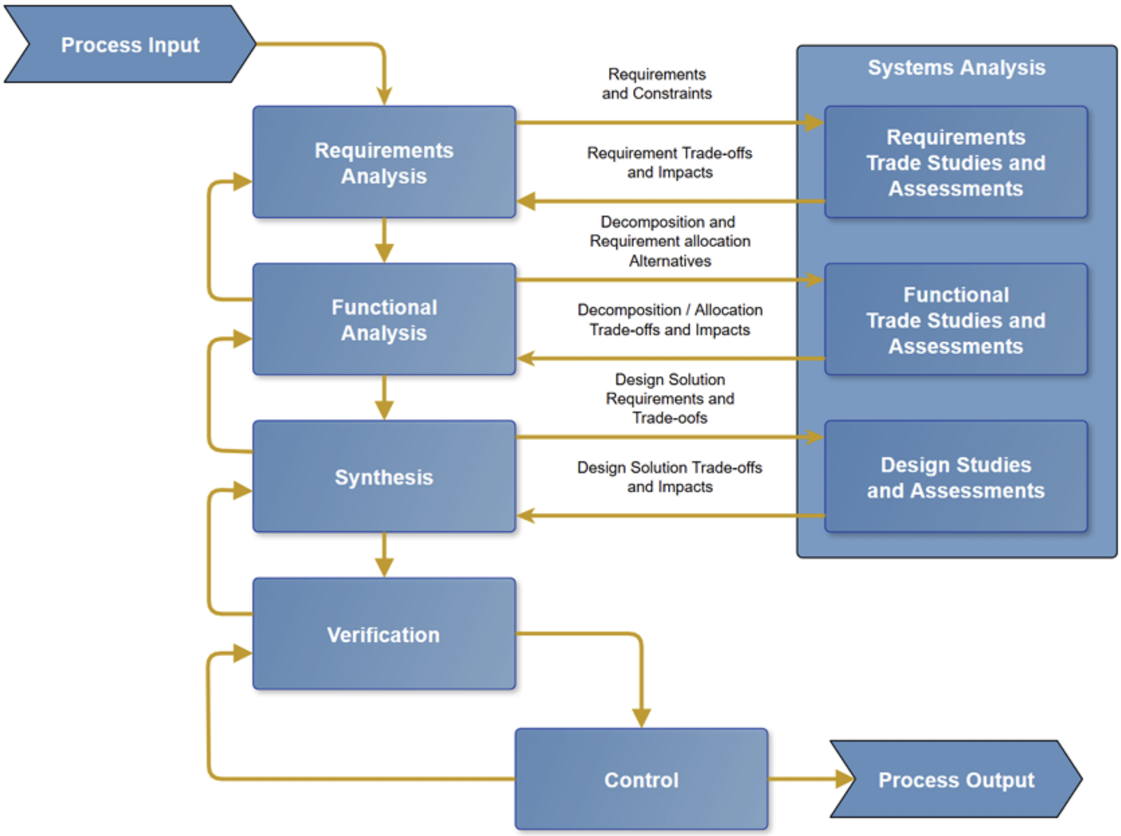
Source: (CASEBOLT et al., 2020)

2.1.1.3 RePoSyD

With its early development starting in 1997, Requirements Engineering, Project Management and System Design (RePoSyD) had its birth in the German naval defense sector on tools named RDD-100 and Design Data Base (DDB).In 2017 it was fully developed as a client-server application and uses a joint reference model to combine System Development and Project Management (BEYERLEIN, 2020). It uses the IEE01220 systems engineering process as a definition and has its own cloud-based tool and modeling language (MAIO et al., 2021).

It is a tool-specific methodology, where the following stages must the followed in sequence: Project Management, Risk Management, System Context, Requirements Development, System Design, Modeling, Hazard Analysis, Physical Design, Verification Management, Configuration Management, Design Management and Design Documentation (BEYERLEIN, 2020).

Figure 3 – SE processes in RePoSyD



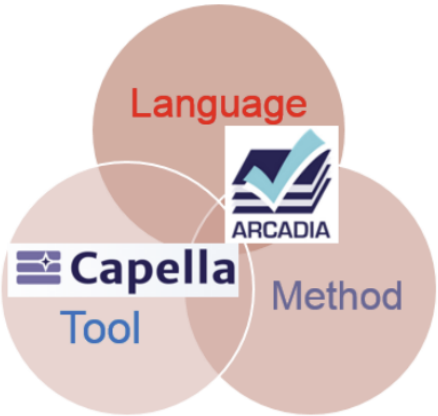
Source: (BEYERLEIN, 2020)

2.1.1.4 ARCADIA

Created by the French aerospace and design company Thales, ARCADIA is an integrated system engineering modeling methodology that uses many concepts present in the SysML and UML languages. It is accompanied by its tool Capella and focuses on having traceability between different engineering levels through the automated exchange of information inside the tool (MAIO et al., 2021). Capella/ARCADIA has been significantly rising in popularity in the aerospace and defense sectors, with companies such as Airbus, Airbus DS and Areva being interested in using this tool (ROQUES, 2016a).

It is structured in successive engineering phases that, following the IEEE 1220 standard, find solutions for three interrelated activities: Need Analysis and Modelling, Architecture Building and Validation and Requirements Engineering. These engineering phases are present inside the Capella tool and are named as Operational Analysis, Systems Analysis Logical architecture and Physical Architecture, while the validation of all these is present in a continuous manner throuout the whole design process

Figure 4 – The three pillars of MBSE with ARCADIA/Capella



Source: (ROQUES, 2016a)

(ROQUES, 2016b).

In the foundational phase, Operational Analysis focus is on identifying and documenting stakeholder needs, without considering specific solutions. It establishes a high-level understanding of system boundaries, key entities, and essential interactions, translating stakeholder expectations into operational activities and constraints. By defining these needs independently of technical specifications, this stage sets the stage for clear requirements and expectations that will guide subsequent design phases.

The System Analysis stage addresses critical questions about the system's required functionality and external interfaces, identifying how the system should perform and interact with external actors. Key activities in System Analysis include formalizing requirements, defining system boundaries, and conducting both functional and non-functional analysis to specify system components, interactions, and data exchanges. Additionally, it involves analyzing capabilities to identify the system's operational modes, functional chains, and behavioral scenarios to ensure comprehensive system definition and alignment with stakeholder expectations.

The Logical Architecture step refines the system by comparing requirements and functional analyses to select Logical Components and outline an initial, moderately detailed view of the architecture. It focuses on guiding the overall design without delving into technology choices, leaving implementation details for the Physical Architecture phase, which will specify the actual components constituting the system. Non-functional constraints, such as safety and performance, are considered only to the extent that they shape the grouping of functions into components.

The Physical Architecture transitions from the abstract components defined in Logical Architecture to concrete, implementable system elements. This phase specifies the physical and technological components that satisfy system requirements, incorporating implementation details like safety and performance constraints. As the final design phase, it prepares the model for construction while allowing flexibility to accommodate future technological advancements, thereby providing a stable blueprint for realizing the system's architecture.

2.2 SYNGAS PRODUCTION AND REFORMERS

Synthesis Gas (syngas) is a term used commonly to refer to the product gas from all sorts of gasification processes, but as described by (WOOLCOCK; BROWN, 2013) "Syngas is a mixture of hydrogen (H2) and carbon monoxide (CO) produced from the gasification of carbonaceous feedstock". It has a variety of uses and applications such as a direct power source or an intermediate in the production of other synthetic fuels, such as the ones seen in Figure 5. Currently, syngas is mainly produced from fossil fuel sources, but biogas is a sustainable and renewable alternative for its synthesis. (WOOD; MOKHATAB, 2008) (WOOLCOCK; BROWN, 2013) (RODDY, 2013).

2.2.1 SynGas Production Methods

In this section, several key methods for SynGas production from biogas are explored, focusing on steam reforming, partial oxidation, dry reforming, bi-reforming, and tri-reforming approaches. Each method has its unique processes, benefits, and challenges, which affect its viability and efficiency in producing hydrogen-rich SynGas.

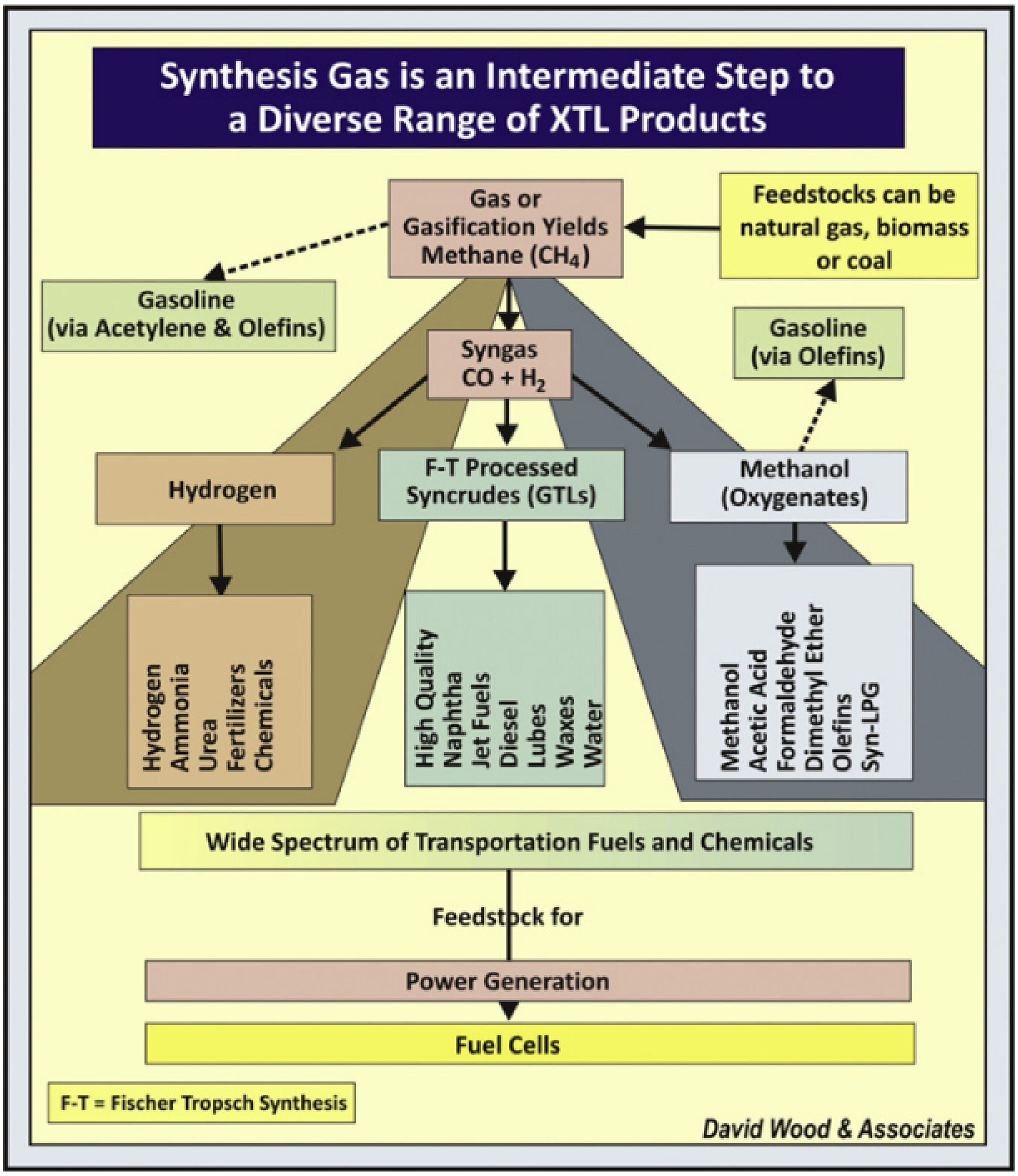
Biogas dry reforming has the potential to be a great contributor to future global hydrogen production from biogas, it is described by equation 1. However, two great drawbacks of using this process for syngas production are its highly endothermic nature and tendency for coke accumulation, which may lead to high operation costs, catalyst deactivation and plugging of the reforming reactor (ZHAO et al., 2020).

$$\mathrm{CH_4} + \mathrm{CO_2} \rightleftharpoons 2\,\mathrm{CO} + 2\,\mathrm{H_2} \qquad \Delta H^\circ = 247 kJ/mol \tag{1}$$

When the CO_2 separation step is not realized in the reforming of CH_4, through the addition of water vapor into the reactor, steam reforming (Equation 2) is achieved. This can lead to a significant reduction in coke accumulation on the catalyst. When CO_2 and steam reforming of methane are combined, the process can be referred to as bi-reforming of biogas (Equation 3). It is less energy intensive than dry reforming, but one disadvantage of using this process is that O_2 must be removed if present in high concentration on the biogas (WOOLCOCK; BROWN, 2013).

$$\mathrm{CH_4} + \mathrm{H_2O} \rightleftharpoons \mathrm{CO} + 3\,\mathrm{H_2} \qquad \Delta H^\circ = 206 kJ/mol \tag{2}$$

Figure 5 – Overview of SynGas as an intermediate in the production of other fuels.



Source: (WOOD; MOKHATAB, 2008)

$$3\,\mathrm{CH_4} + \mathrm{CO_2} + 2\,\mathrm{H_2O} \rightleftarrows 4\,\mathrm{CO} + 8\,\mathrm{H_2} \qquad \Delta H^\circ = 220kJ/mol \tag{3}$$

Partial oxidation (Equation 4) is a highly exothermic reaction that can also be for the reforming of biogas. When the two reactions used in the bi-reforming of biogas, dry and steam reforming (Equation 5), are combined with the partial oxidation reforming reaction, tri-reforming is achieved.

$$2\,\mathrm{CH_4} + \mathrm{O_2} \rightleftarrows 2\,\mathrm{CO} + 4\,\mathrm{H_2} \qquad \Delta H^\circ = -71kJ/mol \tag{4}$$

$$2\,\mathrm{CH_4} + \mathrm{CO_2} + \mathrm{H_2O} + \frac{1}{2}\,\mathrm{O_2} \rightleftharpoons 3\,\mathrm{CO} + 5\,\mathrm{H_2} \qquad \Delta H^\circ = 150kJ/mol \tag{5}$$

Combining these reactions comes with great benefits, there is no need for O_2 removal, coke is inhibited by H_2O and O_2 and lower energy consumption when compared to bi-reforming are a few examples. However, this process is prone to oxidation of the catalysts, causing the oxygen present in the reaction (WOOLCOCK; BROWN, 2013).

Table 1 – Comparison of SynGas Production Methods

Method	**Enthalpy**	**Positive Characteristics**	**Negative Characteristics**
Dry Reforming	247 kJ/mol	Uses CO_2, high yield	High energy, coke issues
Steam Reforming	206 kJ/mol	High H_2 yield	Water demand, high energy
Partial Oxidation	-71 kJ/mol	Exothermic, fast reaction	Lower H_2 yield, requires oxygen
Bi-Reforming	220 kJ/mol	Less coke, efficient	Needs O_2 removal
Tri-Reforming	150 kJ/mol	Inhibits coke, low energy	Catalyst oxidation risk

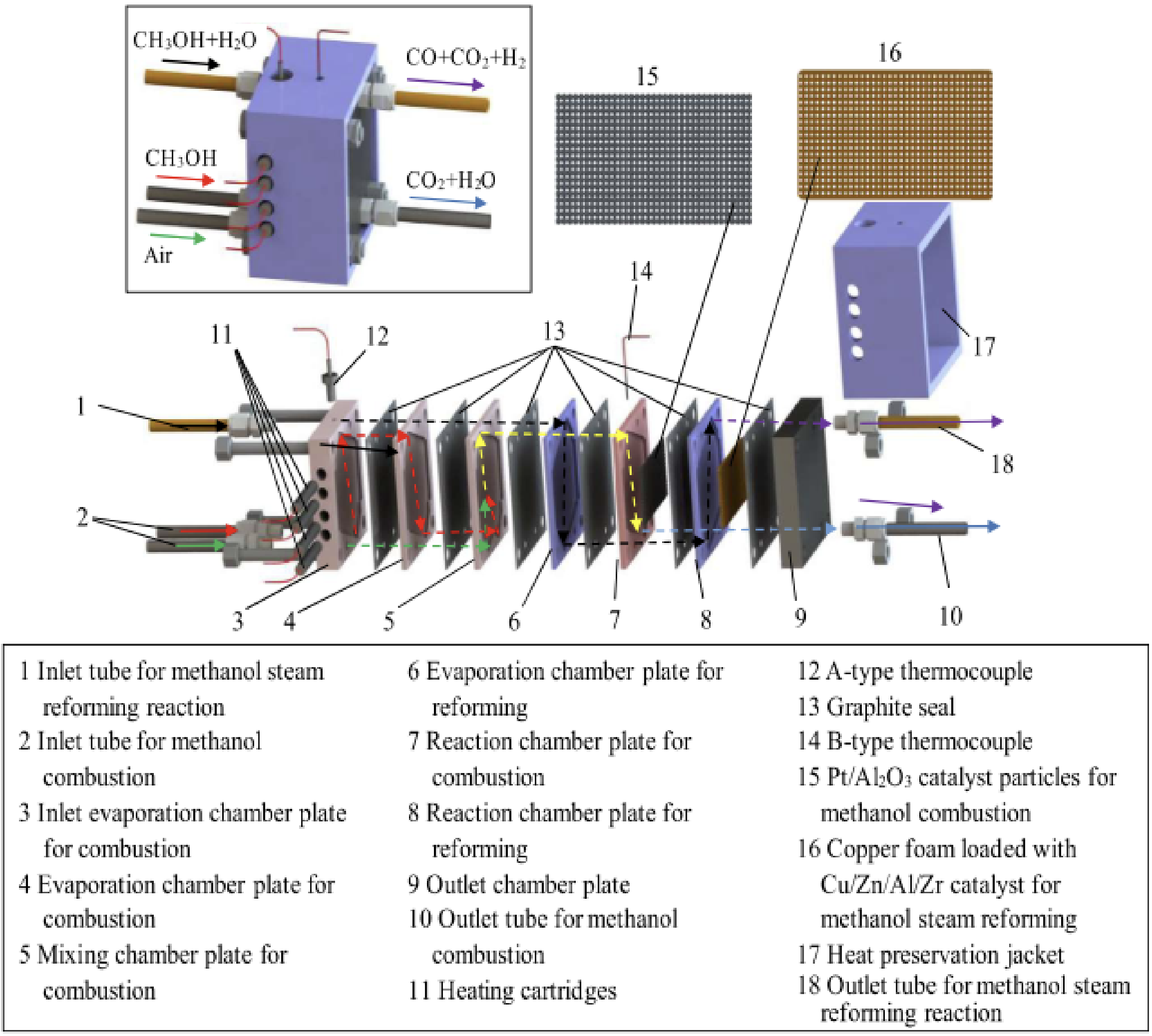
2.2.2 Reactors for SynGas Production

Various types of reactors are utilized to produce syngas from biogas, each tailored to specific process scales, operating conditions, and desired outcomes. Common options include fixed-bed, fluidized-bed, and microreactors, with each offering distinct advantages. Fixed-bed reactors, known for their simplicity and robustness, are often deployed in smaller-scale setups for processes like partial oxidation or steam reforming. In contrast, fluidized-bed reactors are favored for large industrial operations due to their superior heat and mass transfer capabilities, which enhance process efficiency and scalability (WOOLCOCK; BROWN, 2013).

Microreactors, a more recent and uncommon reactor type, they have are an alternative for small-scale or decentralized syngas production. Unlike traditional reactor designs, microreactors exhibit extremely high surface-to-volume ratios, which significantly improve heat and mass transfer. This unique characteristic allows for precise control of reaction conditions, making them particularly suitable for reactions with fast kinetics, such as in the microreactor developed by (ZHENG et al., 2020a) (Figure 22).

The integration of microreactors in syngas production aligns well with the objectives of this thesis, which focus on process intensification and sustainable energy solutions. Their compact design and high performance make microreactors ideal for localized applications where space constraints and energy efficiency are critical. Moreover, their ability to achieve high throughput in a controlled environment ensures consistent product quality, which is essential for subsequent chemical synthesis or energy generation. These features highlight the importance of microreactors in advancing syngas production technologies, particularly in applications that prioritize sustainability, efficiency, and research data collection (ZHANG et al., 2016).

Figure 6 – Structural diagram of self-thermal methanol steam reforming microreactor for hydrogen production.



Source: (ZHENG et al., 2020a)

3 METHODOLOGY

The application of Model-Based Systems Engineering (MBSE) in SynGas system design for this functional design follows a structured, iterative approach, leveraging the capabilities of Capella and the ARCADIA methodology. It begins with the determination of the system's requirements and evaluation of the reformer modeling process. Then it goes into the different modeling levels inside Capella using the ARCADIA methodology (operational analysis, system analysis, logical architecture and physical architecture), culminating in validating all the steps taken throughout the development procedure. The methodology used in this work is heavily based on the works of (ROQUES, 2016a), (MADNI NORMAN AUGUSTINE, 2023), (MAIO et al., 2021) and (ESTEFAN, 2008).

3.1 REQUIREMENTS AND GOALS

The first step when developing such a model inside Capella and the ARCADIA methodology is to define the system requirements and goals. This is made in a somewhat abstract manner, as no physical properties, electronic interfaces or similar concrete properties of the system should be defined in this step (ROQUES, 2016b). The system was defined as a SynGas-generating device that uses natural/biogas for its production, it should contain some sort of data collection interface that allows the researchers to obtain reliable and useful data for analysis and should also allow them to operate and change any parameters that might be necessary to maintain its functioning and to alter operating conditions for different testing setups.

3.2 OPERATIONAL ANALYSIS

The Operational Analysis of the System is the first model phase inside Capella, here "what the system's users must achieve" is defined. This perspective delves into the analysis of operational users by identifying the actors who need to interact with the system, their objectives, tasks, limitations, and the conditions under which they interact. This approach enables the modeling of the necessary high-level operational capabilities and conducting an analysis of operational requirements without explicitly defining the system of interest; in fact, the system is not even referenced at this stage.

There are seven main concepts used in this modeling phase (Figure 7). These were defined by Castro (CASTRO, 2023) as Operational Capabilities are the capabilities of an organization to provide a high-level service leading to an operational objective being reached; Operational Entities and Actors are responsible for realizing these capabilities through the use of Operational Activities; An Operational Activity is a process step carried out to reach a precise objective by an operational entity, which might need to use the future system to do so. Operational Activities should be written in the form: [action verb] + [object]. An Operational Interaction is an exchange of information or unidirectional matter between operational activities; An Operational Process consists of a series of activities and interactions that contribute toward an operational capability. An operational Process captures the flow of a series of Operational Activities; An Operational Scenario is a scenario that describes the behaviour of entities and and/or operational activities in the context of an operational capability. It is commonly represented as a sequence diagram, with the vertical axis representing time.

Figure 7 – Concepts in the Operational Analysis modeling phase.

Source: Author

3.3 SYSTEM ANALYSIS

The perspective presented in this analysis focuses on treating the system as a black box to determine how it can meet the previous operational requirements. This approach involves developing an external functional analysis that is derived from the operational analysis and textual input requirements, and then aligning it with these factors. The Operational Analysis step involves establishing a domain model that is independent of the specific system to be created, allowing stakeholders' needs to be captured at a high level of abstraction. In contrast, the System Analysis level is where the System of Interest (SoI) begins to take form.

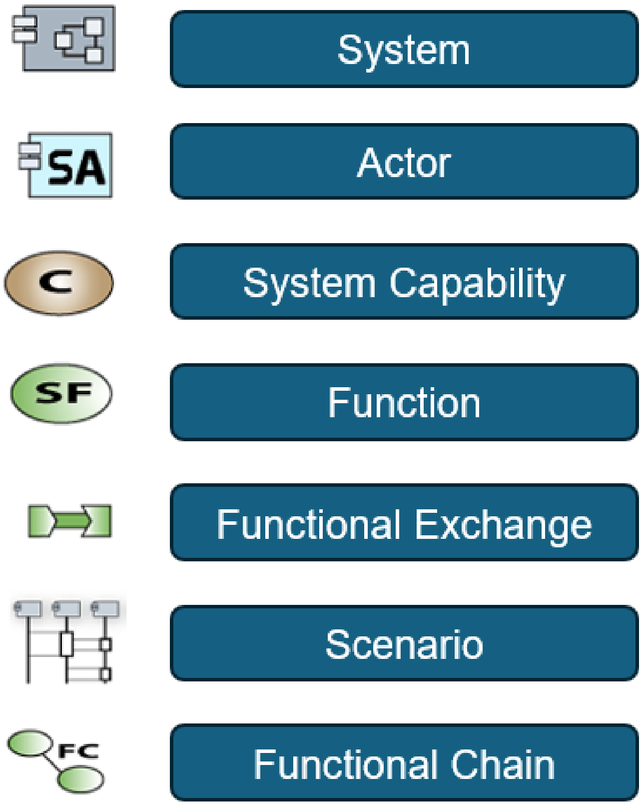
Another seven main concepts can be defined for the System Analysis modeling phase (Figure 8). As defined by Castro (CASTRO, 2023): The System is an organized group of elements that function as a unit (black box) and respond to the needs of the users. The System owns Component Ports that allow it to interact with the external Actors; An Actor is any element that is external to the System (human or non-human) that interacts with it; A System Capability is a capability of the System to provide a high-level service allowing it to carry out an operational objective owns Function Ports that allow it to communicate with the other Functions. A Function can be split into subfunctions; A Function is a behavior or service provided by the System or by an Actor; A Functional Exchange is an unidirectional exchange of information or matter between two Functions, linking two Function Ports; A Scenario is a dynamic occurrence describing how the System and its Actors interact in the context of a System Capability. It is commonly represented in the form of a sequence diagram, with the vertical axis representing time; A Functional Chain is an element of the model that enables a specific path to be designated among all possible paths (using certain Functions and Functional Exchanges). This is particularly useful for assigning constraints (latency, criticality, etc.), as well as organizing tests.

3.4 LOGICAL ARCHITECTURE

In System Analysis, the system's functionality is evaluated as a "black box" to identify its expected behavior and essential exchanges with external actors. The Logical Architecture (LA) phase then "opens the box," establishing a high-level structural decomposition into abstract elements called Logical Components, which address stakeholders' needs through interaction principles and behavior definitions.

Also using the definitions of (CASTRO, 2023), the following concepts for the LA phase can be defined (Figure 9): A Logical COmponent is a structural element within the System, with structural Ports to interact with the other Logical Components and the external Actors. A Logical Component can have one or more Logical Functions. It can also be subdivided into Logical subcomponents; A Logical Actor is any element that is external to the System (human or non-human) and that interacts with it; A Logical Function is a behavior or service provided by a Logical Component or by a Logical Actor. A Logical Function has Function Ports that allow it to communicate with the other Logical Functions. A Logical Function can be subdivided into Logical subfunctions; A Functional exchange is a unidirectional exchange of information or matter between two Logical Functions, linking two Function Ports; A Logical Scenario is a dynamic occurrence describing the interactions between Logical Components and Logical Actors in the context of a Capability. It is commonly represented as a sequence diagram, with

Figure 8 – Concepts in the System Analysis modeling phase.



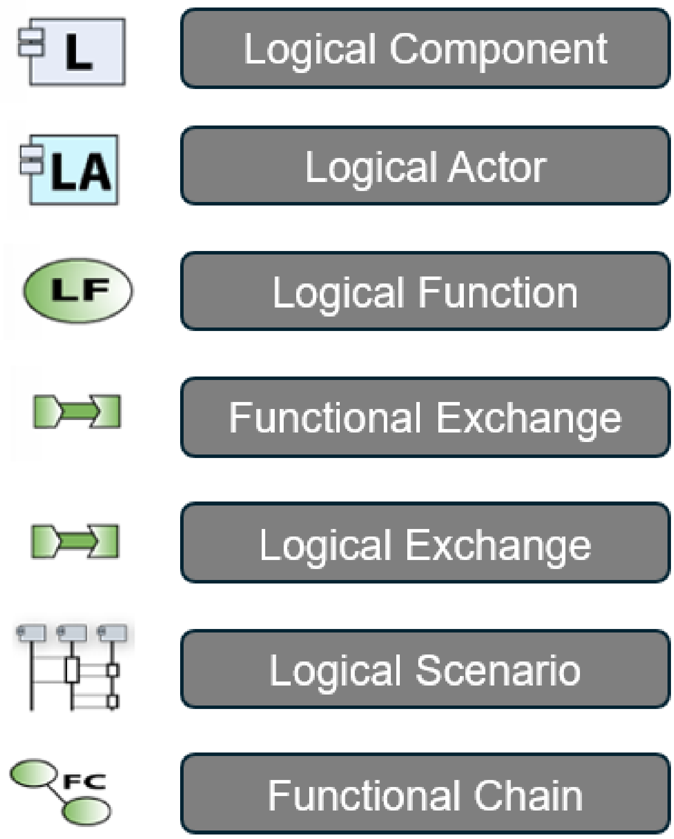
Source: Author

the vertical axis representing the time axis; A Functional Chain is an element of the model that enables a specific path to be designated among all possible paths (using certain Functions and Functional Exchanges). This is particularly useful for assigning constraints (latency, criticality, etc.), as well as organizing tests.

3.5 PHYSICAL ARCHITECTURE

In the Logical Architecture phase, the "black box" approach was used to identify structural elements—referred to as Logical Components—as well as their properties and relationships, while ensuring that all technological and implementation considerations were deliberately excluded at this stage. The transition to the Physical Architecture level marks a shift toward defining the “real” concrete components of the system, where these technological and practical aspects can now be addressed. To facilitate this transition, Capella offers similar step-by-step transitions as those used from Operational Analysis to System Analysis and from System Analysis to Logical Architecture. This approach enables the creation of Physical Functions correspond-

Figure 9 – Concepts in the Logical Architecture modeling phase.

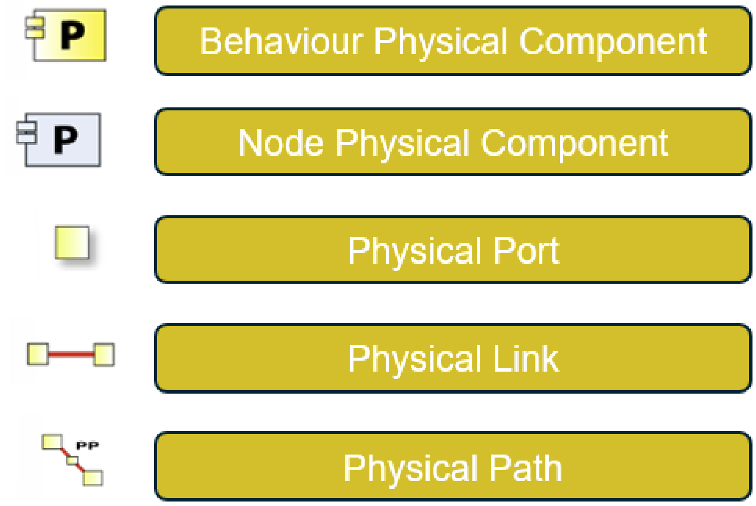


Source: Author

ing to each Logical Function while preserving the continuity of Functional Exchanges and Functional Chains. The main activities involved in this Physical Architecture stage include defining the final architecture and detailed function breakdown, deploying behavioral components, and considering the reuse of existing model elements to optimize efficiency and cohesion across the model.

For the PA phase, the following concepts are organized following the descriptions made by (CASTRO, 2023) (Figure 10): A Behavior Physical Component is a Physical Component tasked with Physical Functions and therefore carrying out part of the behavior of the System; A Node/Implementation Physical Component is a Physical Component that provides the material resources needed for one or several Behavioural Components; A Physical Port is a non-oriented port that belongs to an Implementation Component (or Node). The structural port (Component Port), on the other hand, has to belong to a Behaviour Component; A Physical Link is a non-oriented material connection between Implementation Components (or Nodes). The Component Exchange remains a connection between Behaviour Components. A Physical Link allows one or several Component Exchanges to take place; A Physical Path is an organized succession of Physical Links enabling a Component Exchange to go through several Implementation Components (or Nodes).

Figure 10 – Concepts in the Physical Architecture modeling phase.



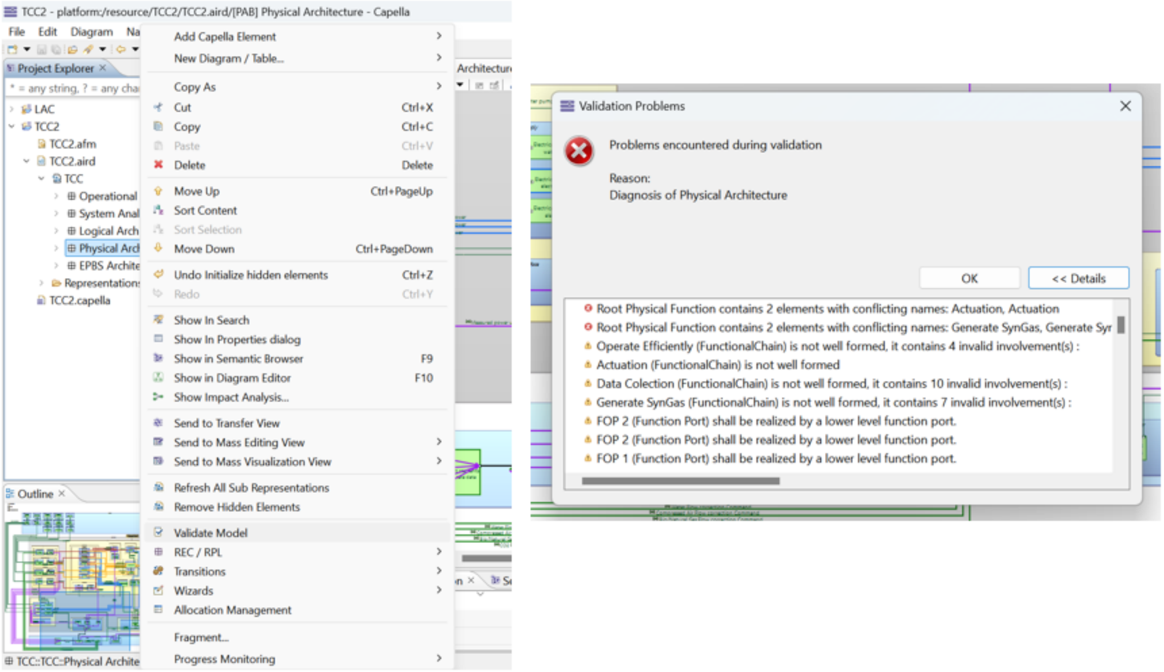
Source: Author

3.6 VALIDATION

As defined by the International Council on Systems Engineering (INCOSE), MBSE is “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases” (FRIEDENTHAL et al., 2014). Consequently, validation was performed continuously during all modeling phases in a cyclic manner. Two distinct approaches were employed for this validation: one incorporated within the Capella software and the other based on existing literature regarding microreforms for the production of SynGas.

The validation of the system within Capella was performed after each design phase, employing the software’s own verification and validation tools to ensure the progressive and effective fulfillment of all specified requirements and design objectives. The outcomes of each phase, including Operational Analysis, System Analysis, Logical Architecture and Physical Architecture, were subjected to verification processes to ascertain their consistency, completeness, and alignment with the model requirements established in preceding stages.

Figure 11 – Error messages provided during the validation process inside Capella, these are used to correct the semantics and overall good functioning of the model.



Problems encountered during validation

Reason:
Diagnosis of Physical Architecture

- Root Physical Function contains 2 elements with conflicting names: Actuation, Actuation
- Root Physical Function contains 2 elements with conflicting names: Generate SynGas, Generate Syr
- Operate Efficiently (FunctionalChain) is not well formed, it contains 4 invalid involvement(s) :
- Actuation (FunctionalChain) is not well formed
- Data Colection (FunctionalChain) is not well formed, it contains 10 invalid involvement(s) :
- Generate SynGas (FunctionalChain) is not well formed, it contains 7 invalid involvement(s) :
- FOP 2 (Function Port) shall be realized by a lower level function port.
- FOP 2 (Function Port) shall be realized by a lower level function port.
- FOP 1 (Function Port) shall be realized by a lower level function port.

Source: Author

Validation inside Capella provides enough to evaluate if semantic and methodology steps were taken correctly, but it does not allow for verification of whether the designed system is physically feasible or not. For that, a validation step with basis on the available literature for reformers and more specifically microreformers for the production of SynGas via biogas was conducted.

The work produced by Zheng et al. (ZHENG et al., 2020a), provided valuable information concerning the design and construction process of a microreactor. The authors created a compact system for the generation of hydrogen through self-thermal methanol steam reforming. As seen in Figure 22, the microreactor uses a set of small chambers sandwiched between thin metal plates where reaction steps such as heating, mixing and combustion take place. This provided a base for the physical design of the SynGas-generating microreactor.

Works such as (WOOLCOCK; BROWN, 2013), (ZHENG et al., 2020b), (KUMAR et al., 2015) and (OLAH et al., 2013), provided insightful data concerning the reaction process that can be used for the production of the synthesis gas. This led to the selection of bi-reforming as the chosen production approach.

4 RESULTS AND DISCUSSION

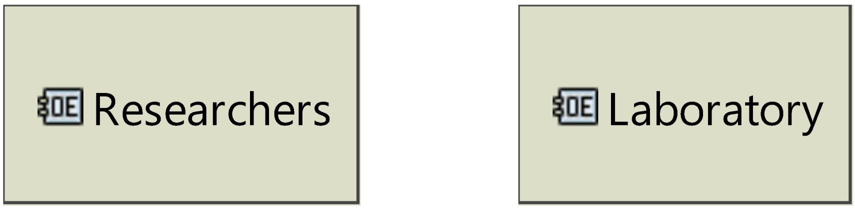
In this chapter, the results from the system modeling phases in Capella will be presented and discussed. The Operational Analysis, System Analysis, Logical Architecture, and Physical Architecture design phases will be sequentially shown. Beginning with Operational Analysis, the chapter outlines the initial stakeholder needs and system capabilities, providing a foundational understanding of system boundaries and interactions. Followed by the System Analysis modeling phase, where the focus shifts to defining the expected behavior of the System and specifying functional requirements. In the Logical Architecture, the model becomes more refined, decomposing the system into abstract components and establishing principles for their interactions without committing to specific implementations. Finally, the Physical Architecture phase translates these abstractions into a concrete design that allows it to be used as a sort of guide to building the reactor in the future. These results were obtained using the methodology described in (ROQUES, 2016a) and (MADNI NORMAN AUGUSTINE, 2023)

This chapter also includes an analysis of the usage of Capella/ARCADIA for this specific problem, including challenges and positive remarks encountered during the design process and possible future works.

4.1 OPERATIONAL ANALYSIS - OA

The first step in the Operational analysis modeling phase was to define the entities involved in the operation of the System. These were determined to be the Laboratory where such a system will be placed and the researchers who will operate and collect data from it (Figure 12).

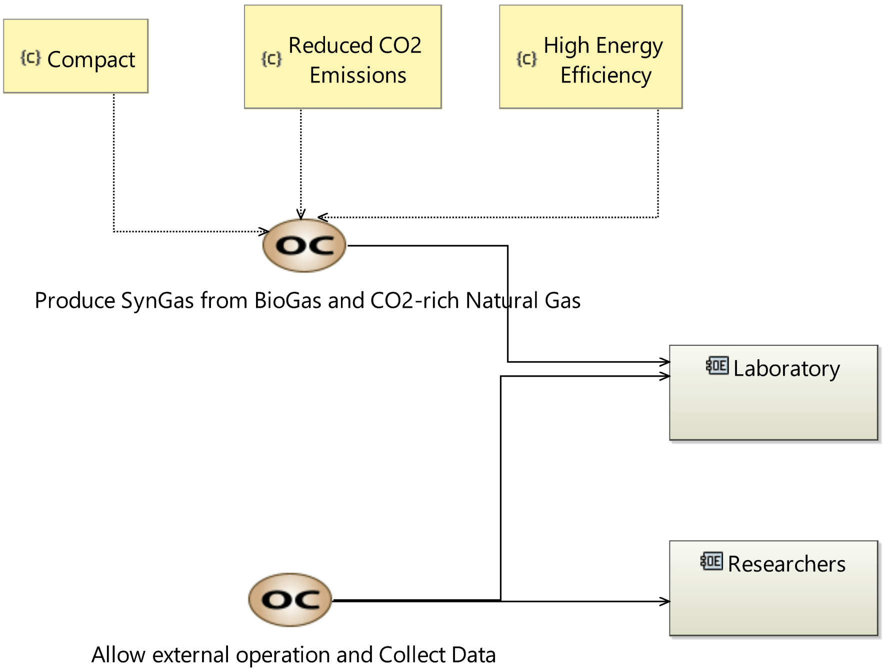
Figure 12 – OA - Operational Entities.



Source: Author

Secondly, the most basic system capabilities must be defined, this was defined on the premises of the design and textual requirements of using biogas for SynGas production, having a data collection interface that allows the researchers to obtain reliable and useful data for analysis and that allows them to operate and change any parameters that might be necessary to operate the system to its full capabilities. This was represented by the Operational Capabilities diagram (Figure 13). The two main cpabilities of the system are defined as producing SynGas from biogas/Natural gas. It is important to note that the Operational Capabilities diagram also contains yellow boxes marked with a "{c}", these are constraints, meaning textual requirements are included in the design, these are being compact, having low CO_2 emissions and a high energy efficiency.

Figure 13 – OA - Operational Capabilities.



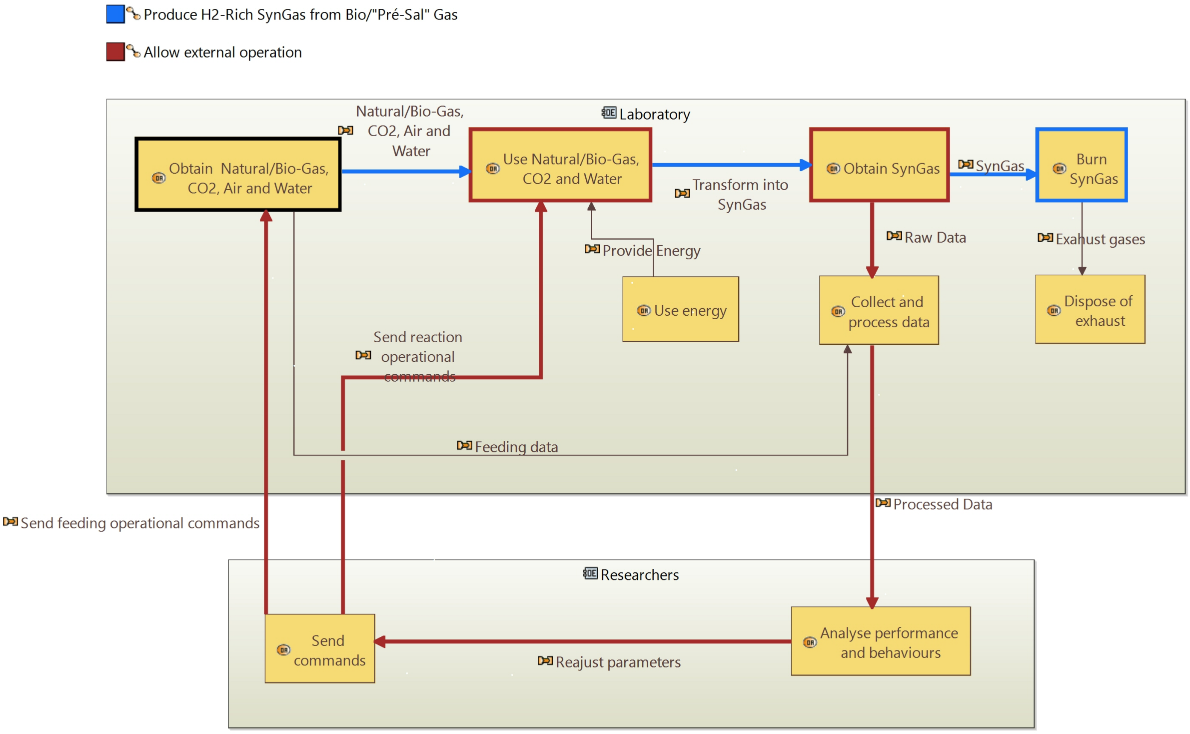
Source: Author

After defining what the system needs to accomplish through its Operational Capabilities, it is necessary to determine how will it achieve this. This is done through the creation of Operational Activities, here the basic steps to generate SynGas, the obtaining of the necessary reagents and the data collection routine are defined in the Root Operational Activities Diagram (Figure 29, Appendix A). These activities are then organized and linked to the Operational Entities that are responsible for them. Activities were divided into two major subgroups, Energy Activities which include the obtention of reagents and the generation of SynGas, and Data Activities which are related to the acquisition of data and control of the system.

The interactions between all activities are also defined and can be seen in the comprehensive Operational Architecture diagram (Figure 14). In this diagram two operational chains are also defined: Produce H_2 rich SynGas and Allow for External Operation. These show the function interaction chains necessary to complete the aforementioned capabilities.

In this design phase the system follows the following logic: first the reagents must be collected, they are then used with the help of an energy (heating) supply to produce SynGas. The rection products are then to be burned and dispoded of, while a data collection system is used to store all usefull data and provide information for the researchers to operate the system and make any necessary changes.

Figure 14 – OA - Operational Architecture.

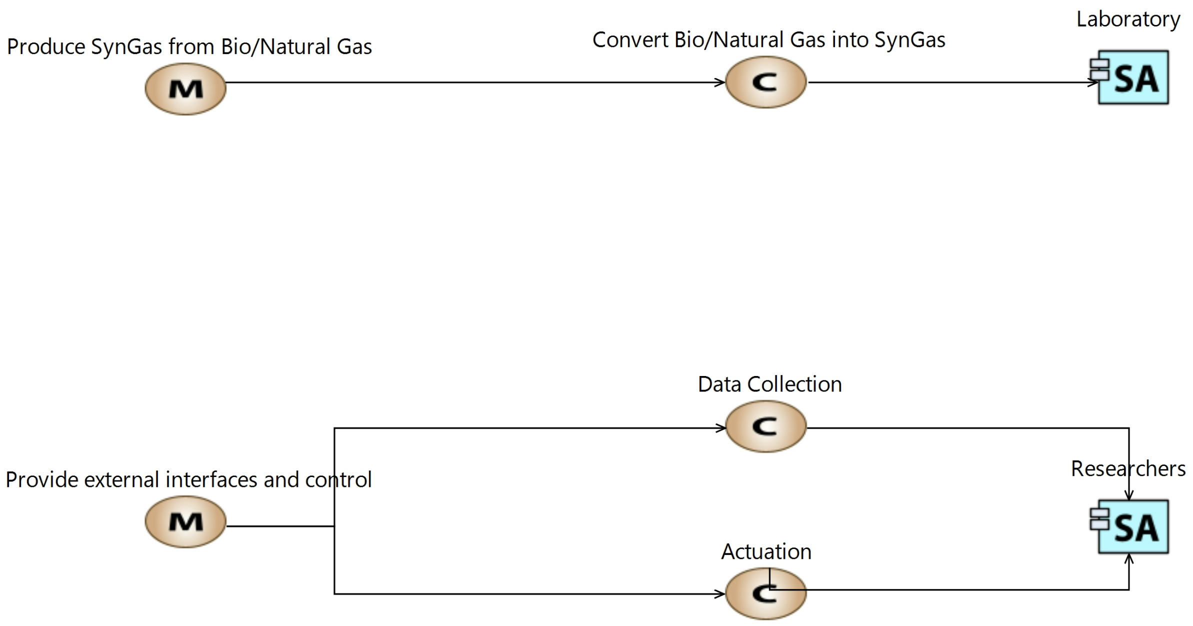


Source: Author

4.2 SYSTEM ANALYSIS - SA

In this phase, the previously defined Operational Capabilities are refined and restructured as System Missions, which are further broken down into specific Capabilities. For instance, the overarching Mission Produce SynGas from biogas was expanded into the more detailed Convert biogas into SynGas Capability, focusing on the core transformation process. Similarly, the Mission Provide external Interfaces and Control was subdivided into two distinct Capabilities: Actuation, which addresses the control mechanisms for operational processes, and Data Collection, which handles the acquisition and processing of system performance metrics (Figure 15).

Figure 15 – SA - Mission and Capabilities Diagram.



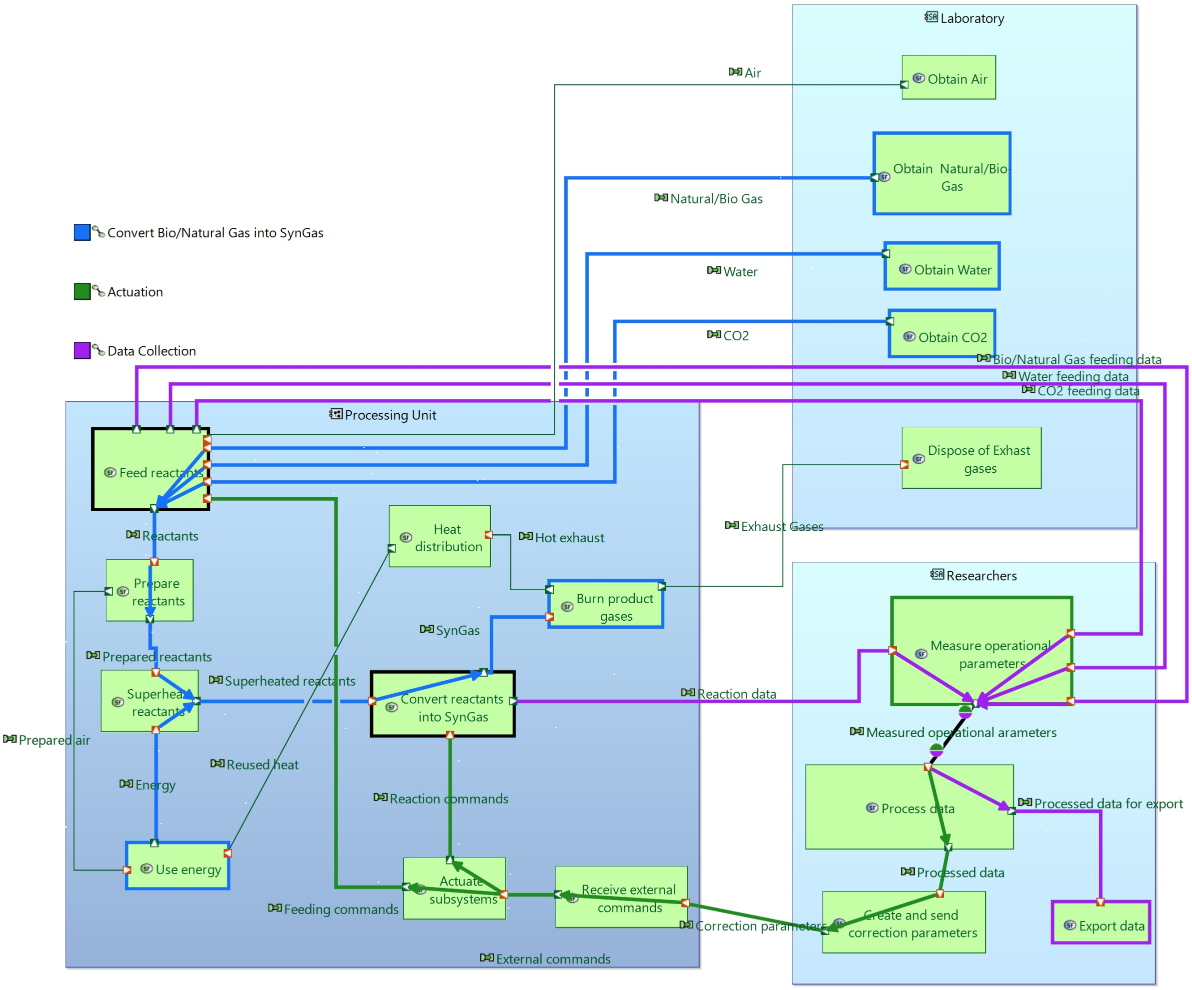
Source: Author

The functions defined for the Operational analysis phase must also be updated to accommodate the requirements of the System Analysis. These new functions can be seen on the SA Root System Function diagram (Figure 30 Appendix A). The functions colored in green belong to the main system, while the blue ones are part of the external actors' responsibilities. Here the functions related to data collection and control are further developed and specified.

These refined functions are then allocated to an external actor or to the system itself and have their interactions defined. This can be seen in the System Architecture diagram (Figure 16), where the complexity significantly increases from the Operational Architecture. Functional chains are also defined for each of the three systems' Capabilities.

The obtaition and feeding of reagents have been discretized and are allocated to the laboratory and processing unit respectively. Heat generation is also better described, as well as data collection and actuaation that now have extra function boxes.

Figure 16 – SA - System Architecture Diagram.

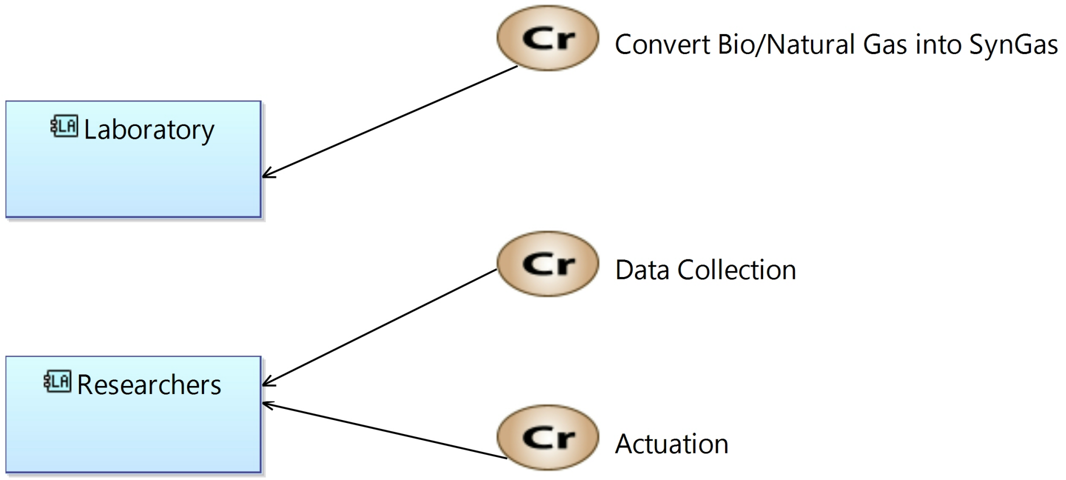


Source: Author

4.3 LOGICAL ARCHITECTURE - LA

In a similar procedure, the Logical analysis phase begins with an update of the system's Capabilities, here they are attributed to one of the previously defined entities (Figure 17).

Figure 17 – LA - Capabilities Diagram.



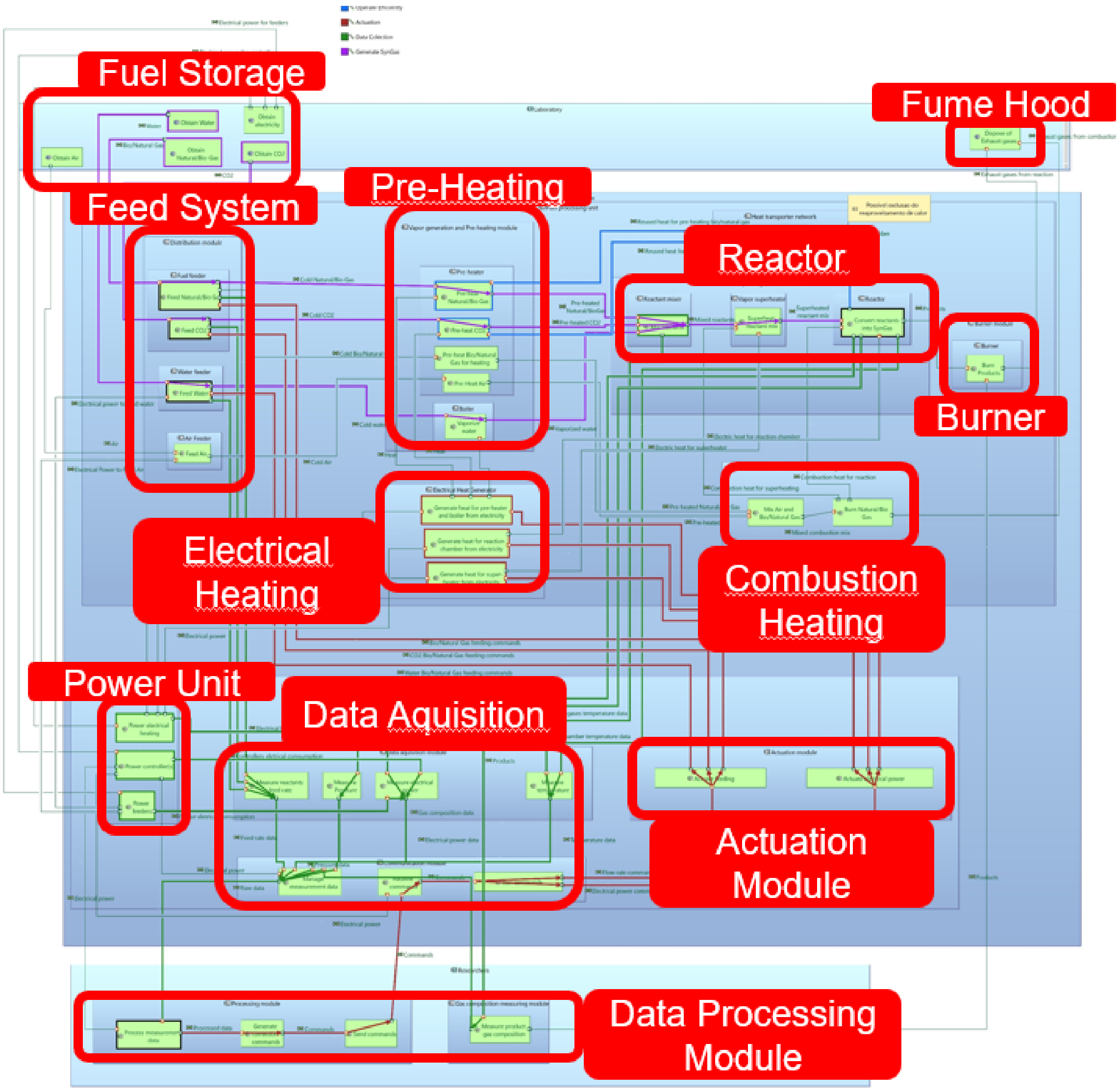
Source: Author

In this step, it is also necessary to define System Components, that is, subsystems that can placed inside the main system or also inside external entities that will in turn house necessary functions. From this phase onwards, the microreactor produced by (ZHENG et al., 2020b) was used as a strong inspiration for the design. The system was divided into two main subsystems, the fuel processing unit and the electronic control unit, which are then further detailed into smaller components as depicted by the Component Structure Diagram (Figure 33), these are in charge of housing components for data acquisition, sensors, heating, reagent transport and mixing and all other necessary functions.

After such components are defined it is possible to allocate the Logical Functions (Figure 31 Appendix A) among them. This is done on the Logical Architecture Diagram (Figure 18), where the envisioned reactor starts to take shape.

Besides de already defined fuel storage and and feeding susbsyetms, there are new additions on the logical architecture diagram. After feeding the reagents flow into a pre-heating section and then into the reactor and burner for discposal. Heating comes from two different sources: initial electric heating and combustion of part of the obtained biogas for the whole duration of the reaction. Data aquisition, data processing, actuation and power unid modules have also been defined.

Figure 18 – LA - Logical Architecture Diagram with indications.



Source: Author

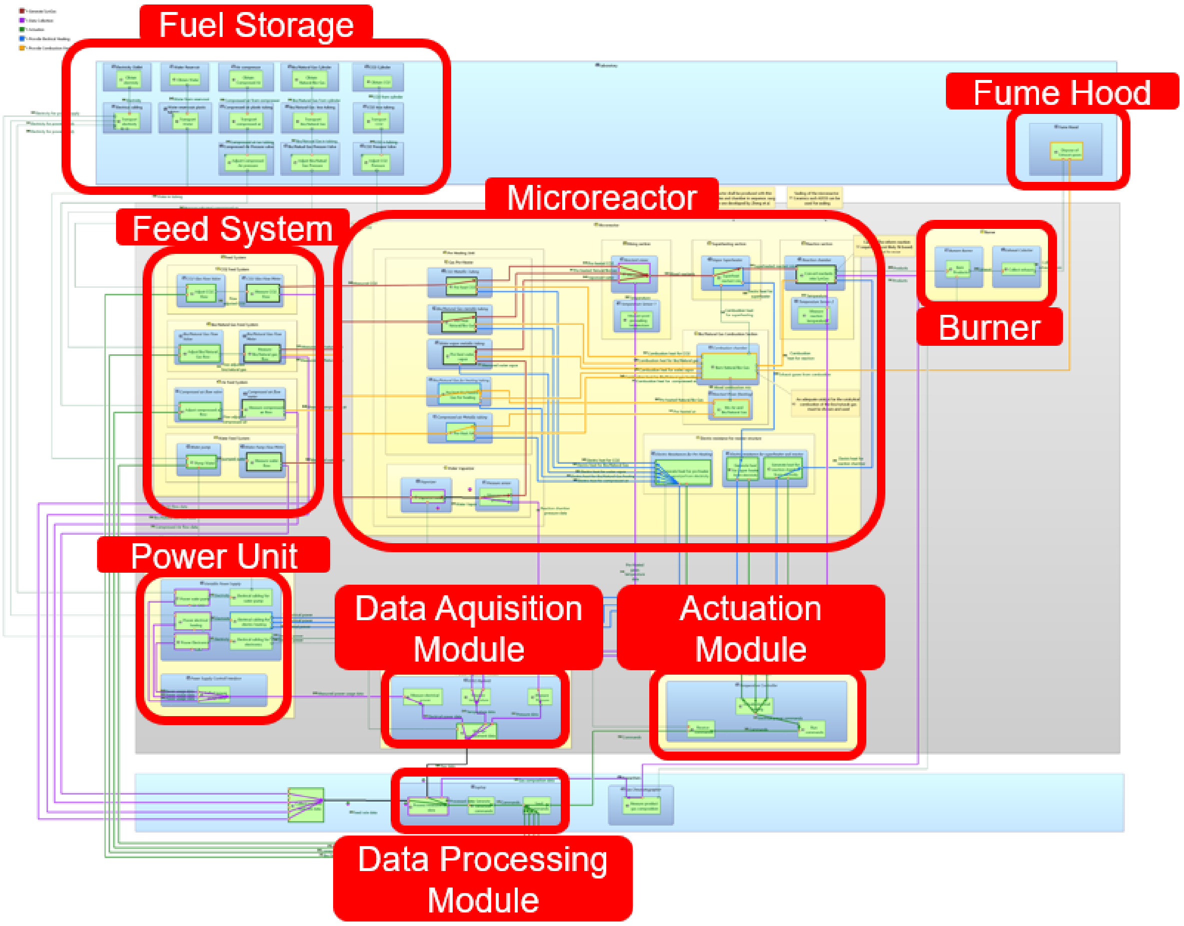
4.4 PHYSICAL ARCHITECTURE

The final modeling phase, Physical Architecture (PA) culminates in the architecture of a fully defined system that can used for its actual construction. This begins with the detailing of the system's components, here they are divided into two categories: Implementation and Behavioral Components. The first is directly tasked with one or more Physical Functions, while the latter provides material components necessary for the function of Behavioral Components and "houses" them. These newly defined components can be seen on the Implementation Component Diagram (Figure 34) and Behaviour Component Diagram (Figure 35).

The system's functions are updated in the same manner as before and can be seen on the Physical Function Diagram (Figure 32). The functions colored in white are imported from the LA phase, while the ones in green were defined at the PA.

The now detailed Physical Functions must be attached to a Behavioral Component that is in turn allocated to an Implementation Component or an external entity. This led to the creation of the Physical Architecture Diagram (Figure 19), which showcases all of the defined structures, functions and interactions through a complete system without any abstractions.

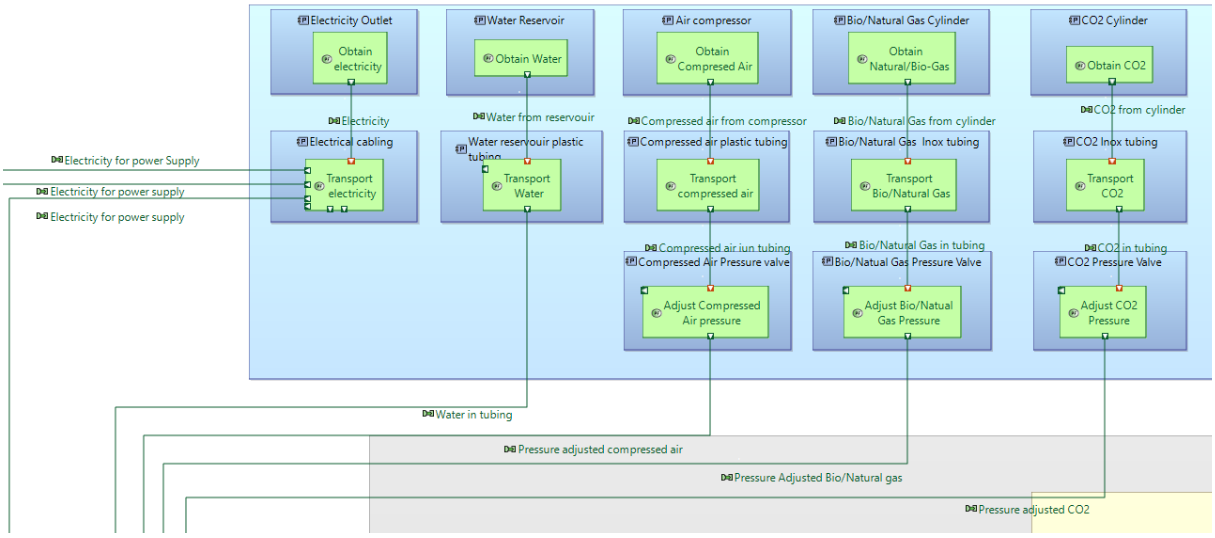
Figure 19 – PA - Physical Architecture Diagram with subsystem indications.



Source: Author

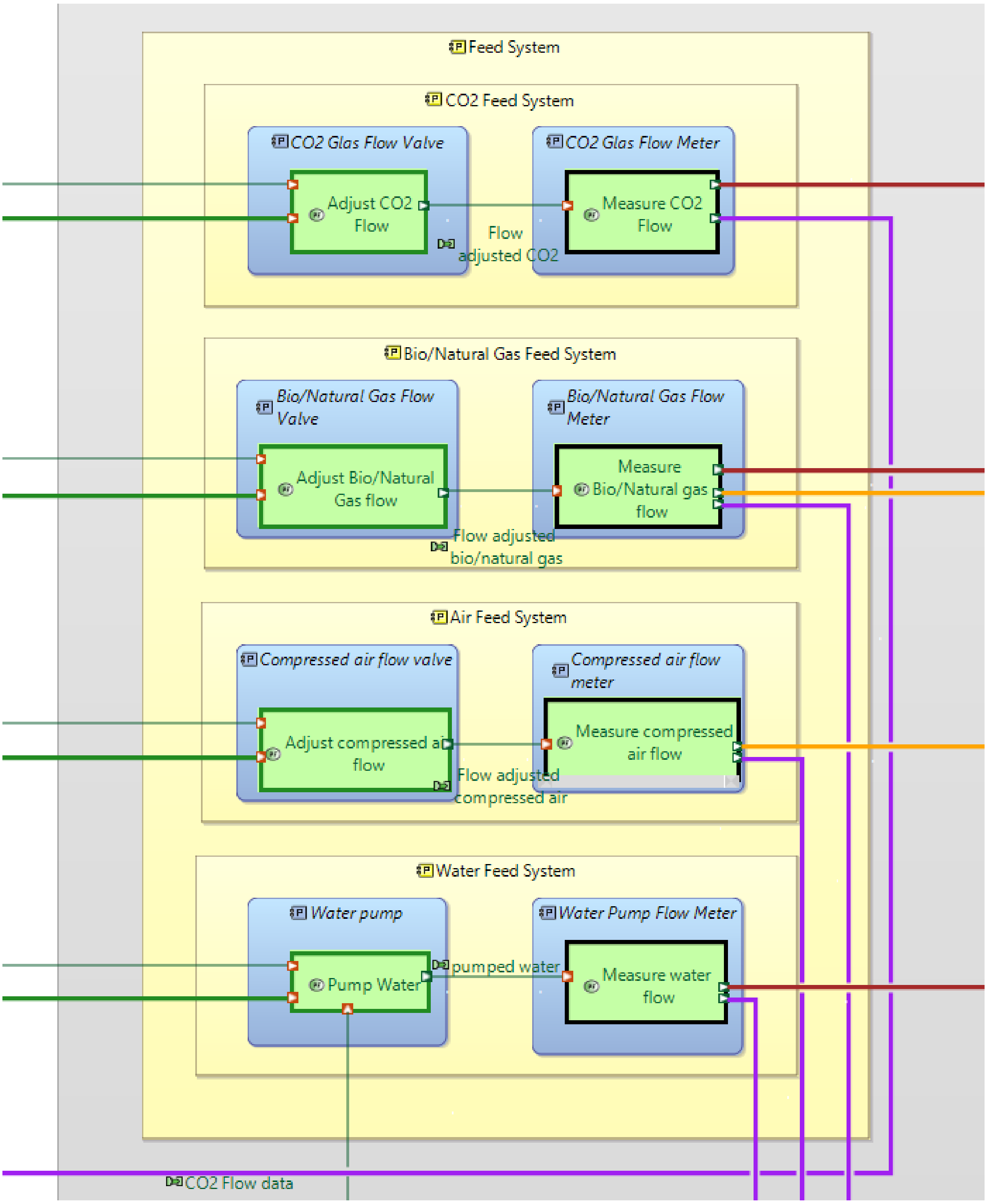
The production of SynGas begins of course with the obtention and storage of the necessary reagents and energy. This is represented on the diagram through the Fuel Storage subsystem (Figure 20). The gas cylinders, water reservoir and electricity source storage and transportation components are represented here. The reagents are then transported to the reactor through the feed system (Figure 21). Where the gases are flow adjusted with valves and water is pumped.

Figure 20 – PA - Fuel Storage System in detail.



Source: Author

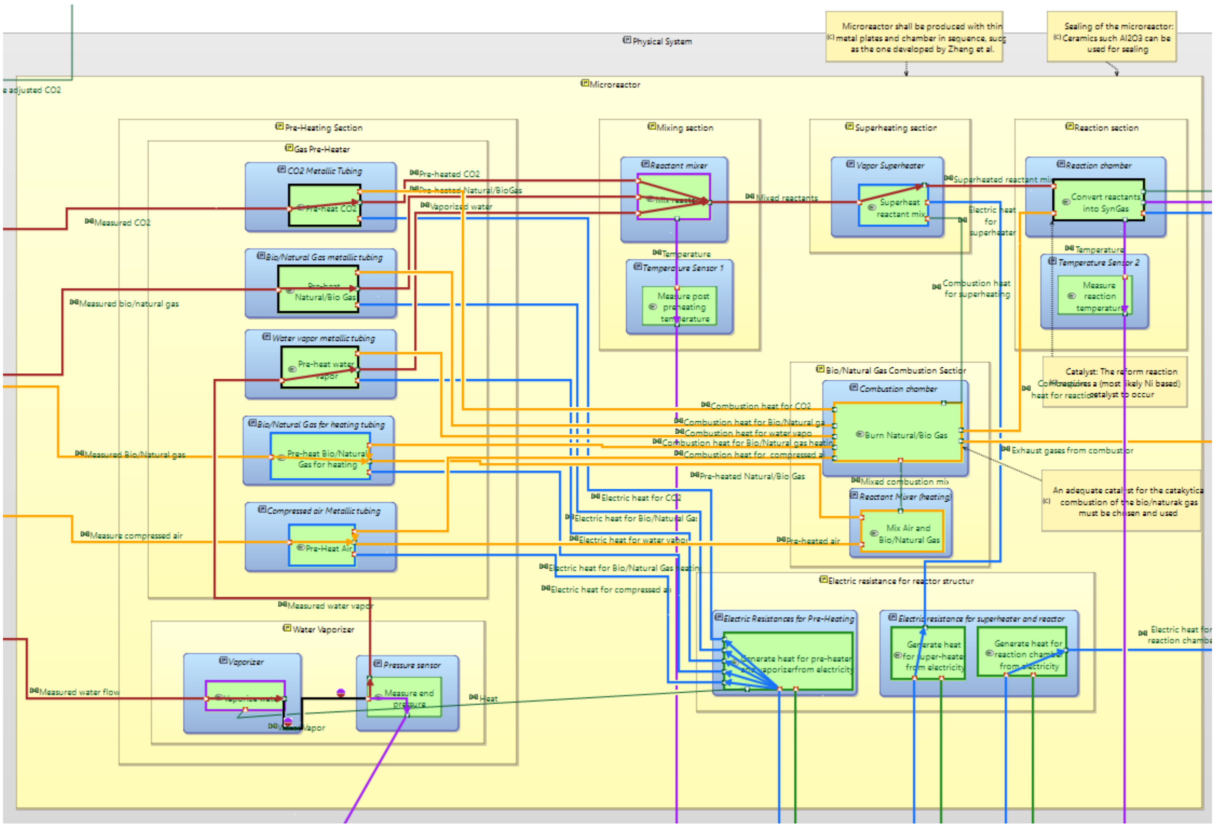
Figure 21 – PA - Feed System in detail.



Source: Author

These reagents are then fed into the main part of the whole system, the microreactor itself. As previously described it consists of a series of small chambers sandwiched between thin metal plates. The first of which is meant for pre-heating the reagents, one detail is that water must first be vaporized in its section. After pre-heating the reagents are then mixed and finally set into the reaction chamber, where the bi-reform into SynGas occurs. The microreactor structure also houses sections for electric and combustion heating. This meant for initial heating of the system and continuous heating during operation respectively.

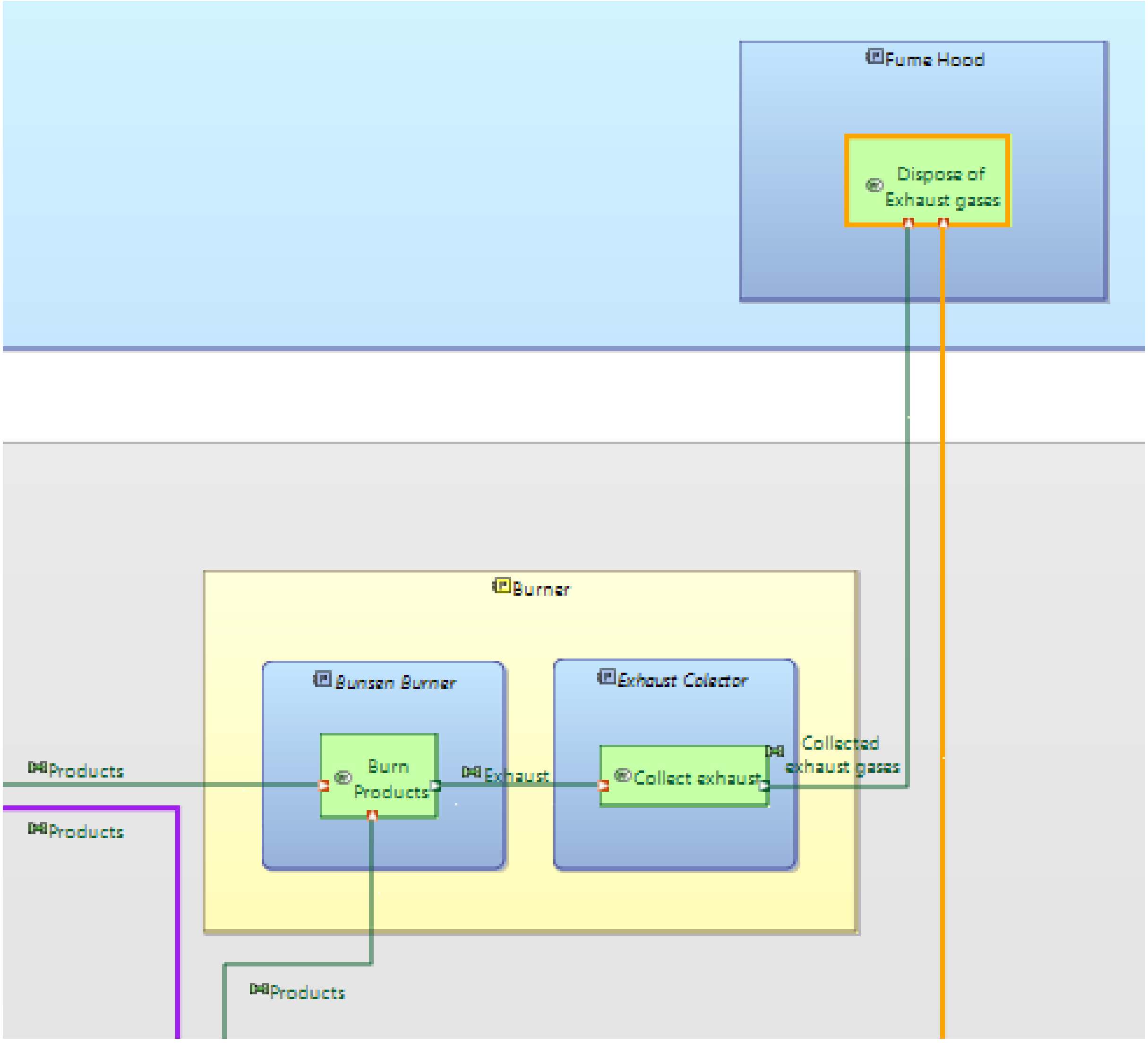
Figure 22 – PA - Microreactor in detail.



Source: Author

After the reaction is complete, the researchers can choose to direct the product gases in one of two ways: flow into a gas chromatographer for composition analysis or flow into a burner. It is not desirable to store the products, as they shall be produced in small quantities only sufficient for analysis and also may contain hazardous carbon monoxide. The burned gases are then sent into a fume hood for exhaustion (Figure 23).

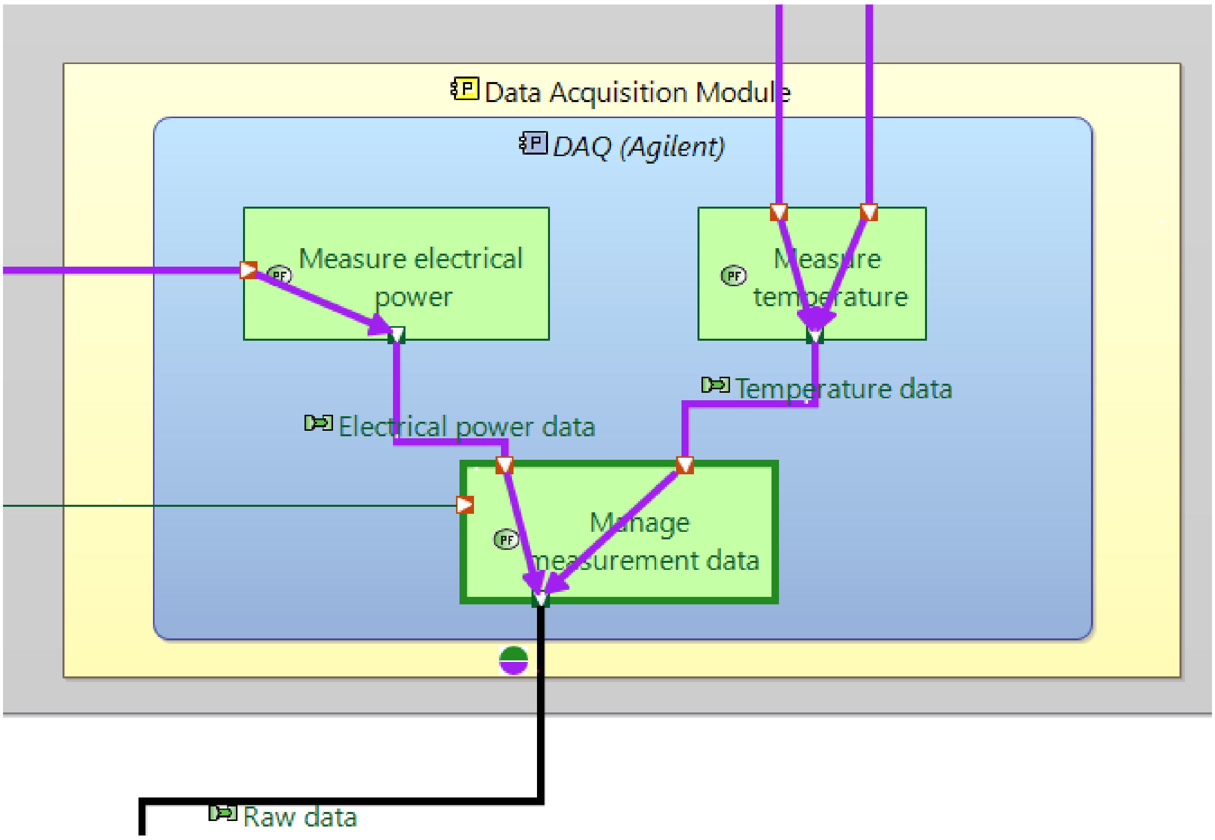
Figure 23 – PA - Burner and Fume Hood.



Source: Author

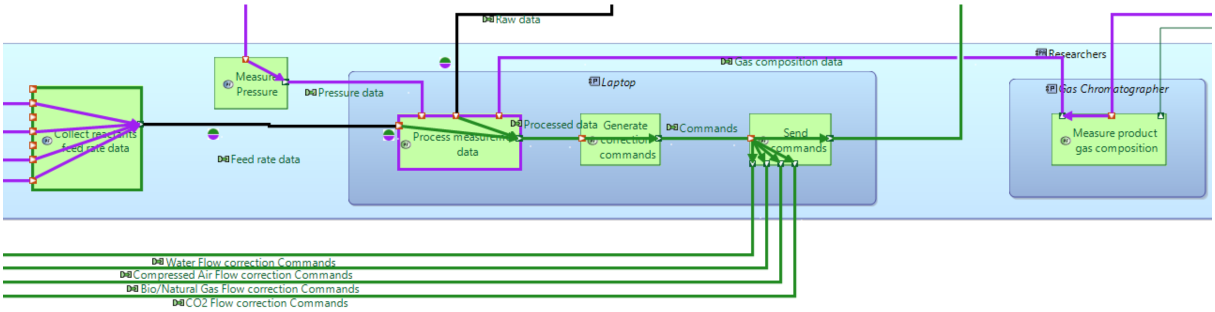
Concerning the data aspect of the design, the Data Acquisition module (Figure 24) is responsible for collecting electrical consumption and temperature data obtained from the power unit and sensors inside the reactor. This data can then be processed in the Data Processing MOdule (Figure 24), which physically corresponds to a computer operated by the researchers, here temperature and electrical consumption data are analyzed together with pressure and gas composition data that must be manually collected from pressure gauges and a gas chromatographer respectively.

Figure 24 – PA - Data Acquisition Module in detail.



Source: Author

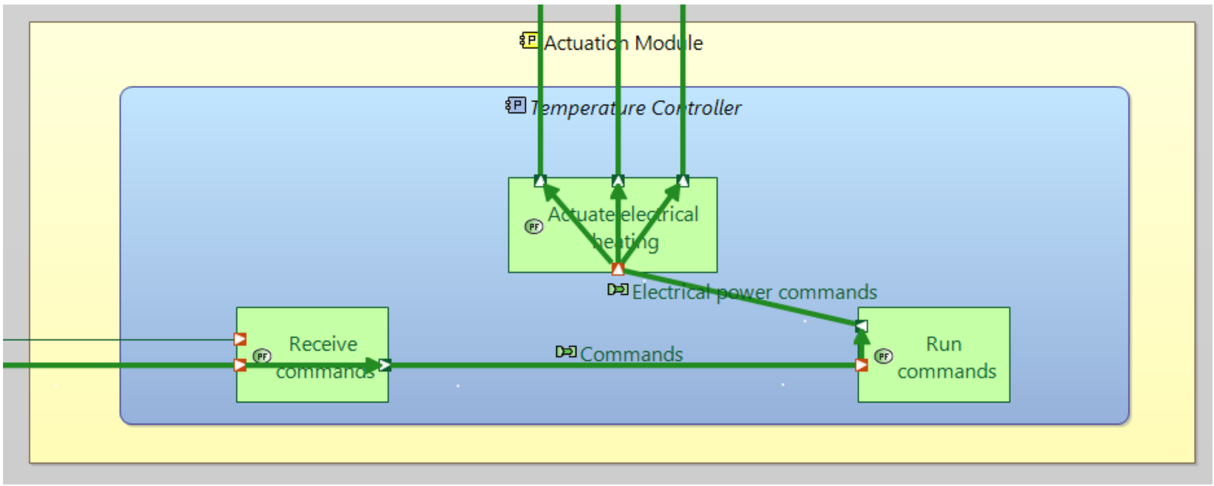
Figure 25 – PA - Data Processing Module in detail.



Source: Author

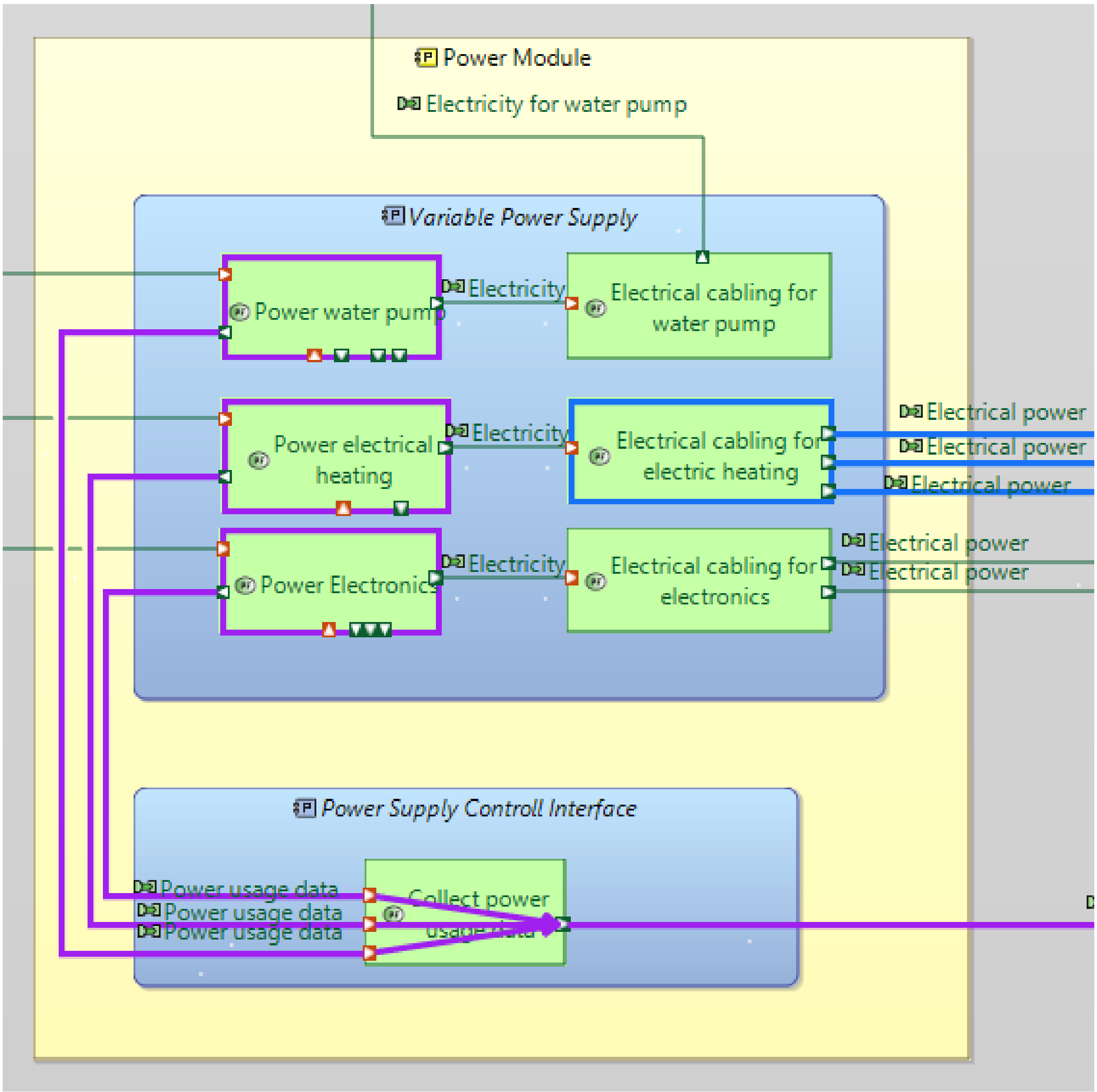
The temperature control of the electric resistance used is realized by the Actuation Module 26, to which the researchers will set a temperature value to be maintained. This actuator, electric resistances and sensors used need all to be powered by electricity provided by the Power Unit (Figure 27).

Figure 26 – PA - Actuation Module in detail.



Source: Author

Figure 27 – PA - Power Unit in detail.



Source: Author

4.5 ANALYSIS

Through the use of ARCADIA and the Capella software, the physical design of a microrreformer for the production of SynGas from biogas was developed. The implementation of the methodology allowed for a step-by-step design process where a somewhat simple concept was intricately explored and defined. Perhaps the main advantage of using such an approach is that "forgetting" to add components, subsystems and mechanisms becomes incredibly difficult.

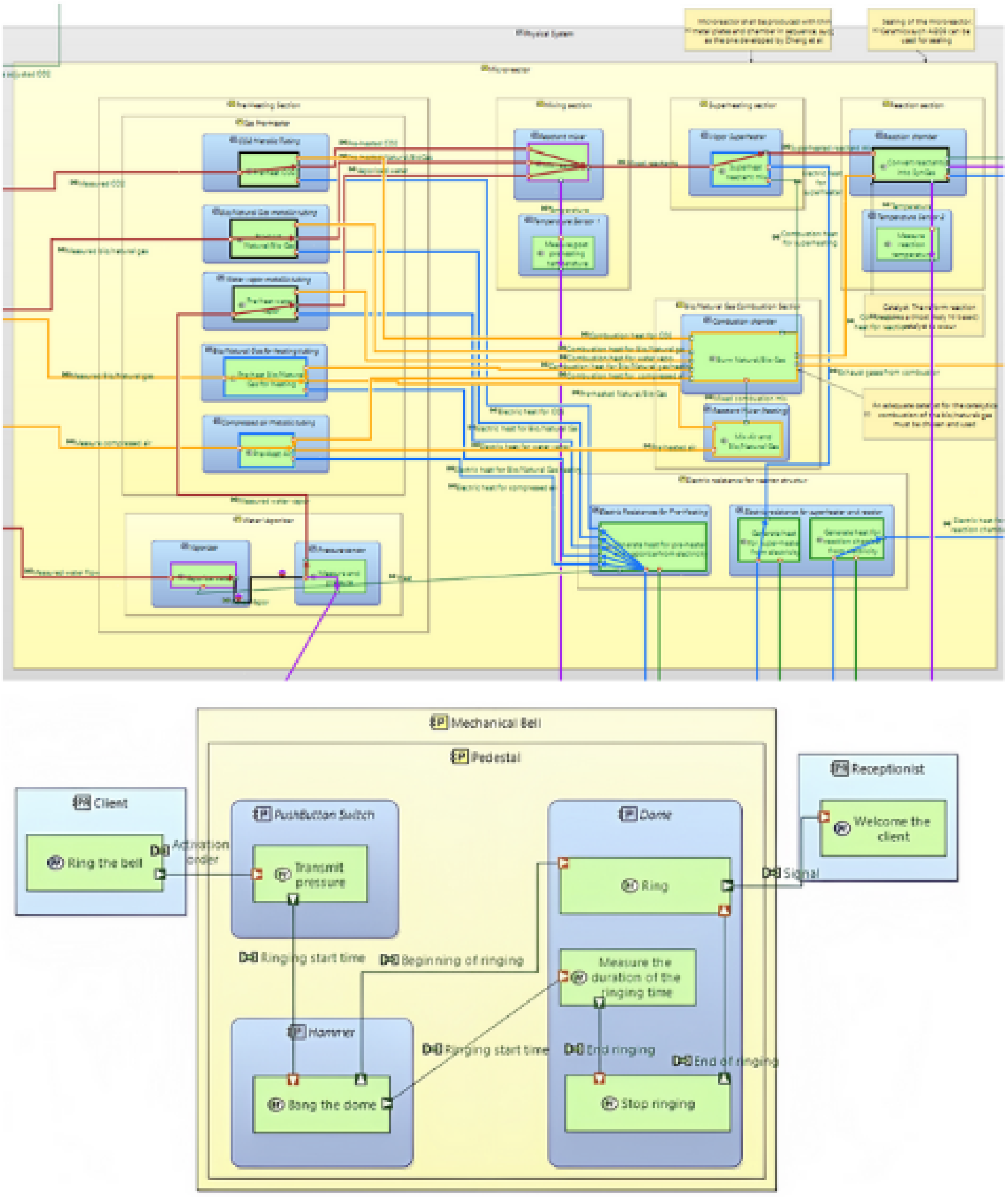
Capella provides great flexibility on how to approach the design process. It is not necessary to develop all modeling phases if one so wishes. In this functional design, all steps were explored to fully understand and analyze the methodology in all its aspects. But if such a reactor would be constructed from the ground up and this would be the only objective in place, constructing the system with a beginning on the logical phase would be recommended. The most basic premises of the system developed during the Operational and System Analysis phases were already known in its conception. Another positive aspect of using Capella was the ease of presenting the progress in development to personnel that was not directly involved in using the methodology. The color schemes and diagram used make it simple for a non-specialized person to understand all the data provided with a brief explanation.

The developed reactor design aligns closely with other similar designs found in the literature, such as the microreactor developed by (ZHENG et al., 2020a). This design not only incorporates the structural and operational efficiencies demonstrated in comparable systems but also effectively supports the bi-reforming reaction, as highlighted in the works of (WOOLCOCK; BROWN, 2013), (KUMAR et al., 2015), and (OLAH et al., 2013). These references provide a strong foundation for validating the reactor's capability to facilitate bi-reforming, ensuring compatibility with established methods.

When compared to the work of (BARON et al., 2023), where the case stufy of a counter bell is described, it is possible to see that similar diagram and procedures where formulated. Even though the described system's are intrisicantelly different, the same methodology was used and results that follow the same framework were obtained, as is expected with the ARCADIA methodology. As an example one can observe the similarities between the physical architecture diagrams (Figure 28): even though the scale of the analysed systems differ greatly, they share the same organization and display method and overall content. Being that both desbribe their respective systems in detail without defining component specifications or materials.

Overall, using this methodology and the accompanying program allowed for the successful development of the desired system with a constant and direct development pace. One of the few drawbacks encountered was the difficult positioning of diagram blocks and interaction lines, which in more complex diagrams may become time-

Figure 28 – Comparison between physical architetcure diagrams produced in this work (top) and by (BARON et al., 2023) (bottom).



Source: Author and (BARON et al., 2023).

consuming and hard to handle. It is also not possible to fully define materials, product specifications, flow measurements, heat transfers or any other sort of quantitative value for components inside Capella, which means that such definitions must be made outside of the software after completing the system analysis using Capella/ARCADIA.

5 CONCLUSION

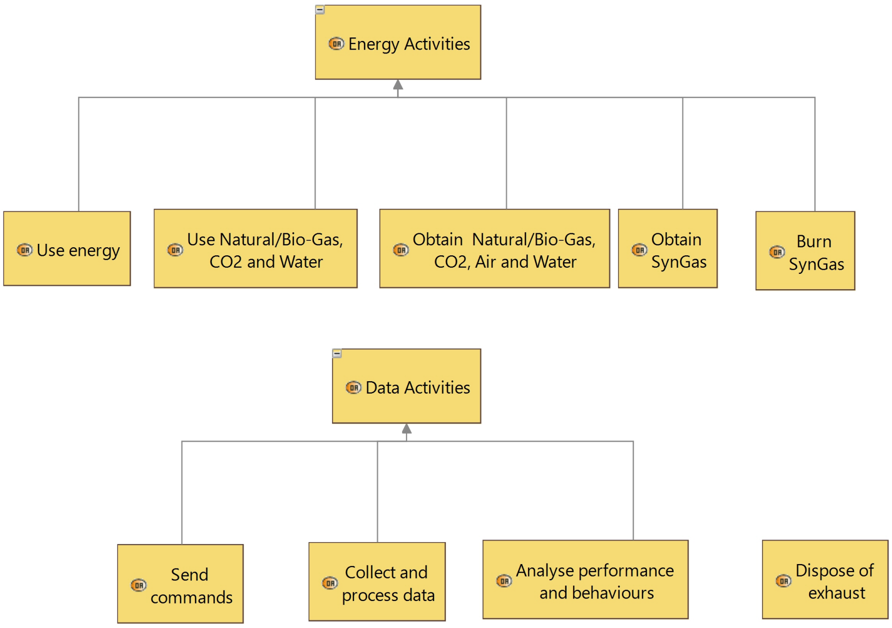
The demand for sustainable energy solutions has grown rapidly, making SynGas production from biogas an attractive alternative to fossil fuels. The objective of this study was to model a micro-reformer for SynGas production, capturing operational, functional, and physical system architectures to align the design process with key requirements and needs using Model-Based Systems Engineering (MBSE) within Capella/ARCADIA. A structured and efficient approach was developed to streamline design complexities, reduce errors, and enhance decision-making across each stage of the reformer's development.

Results indicate that each modeling phase provided crucial contributions to the system's design. In Operational Analysis, initial needs, system boundaries, and core interactions were identified to set a initial understanding of the system. System Analysis refined this by integrating functional requirements and defining the anticipated behaviors for the System, establishing guidelines for system responses to external interactions. Moving into Logical Architecture, the model introduced logical components and clarified the relations between them, shaping a cohesive system without physical implementation details. Finally, in Physical Architecture, these abstractions were converted into specific, implementable components, laying a stable groundwork for potential reactor construction and functionality.

This approach in Capella/ARCADIA offers a reliable, adaptable framework that remains consistent with the functional design's objectives. Further definition of specific components , materials and quantitative values for energy use and flow of reagents is necessary to build the system physically, but the model provides a strong foundation for work. Future research should include further detailing of the physical architecture, more detailed descriptions of the actuation done manually by the researchers, definition of components and materials and incorporation of aspects regarding safety regulations, maintenance and future disposal of the system. It is also relevant to develop processes such as simulations during the validation cycle to fully refine the system and introduce quantitaive performance metrics.

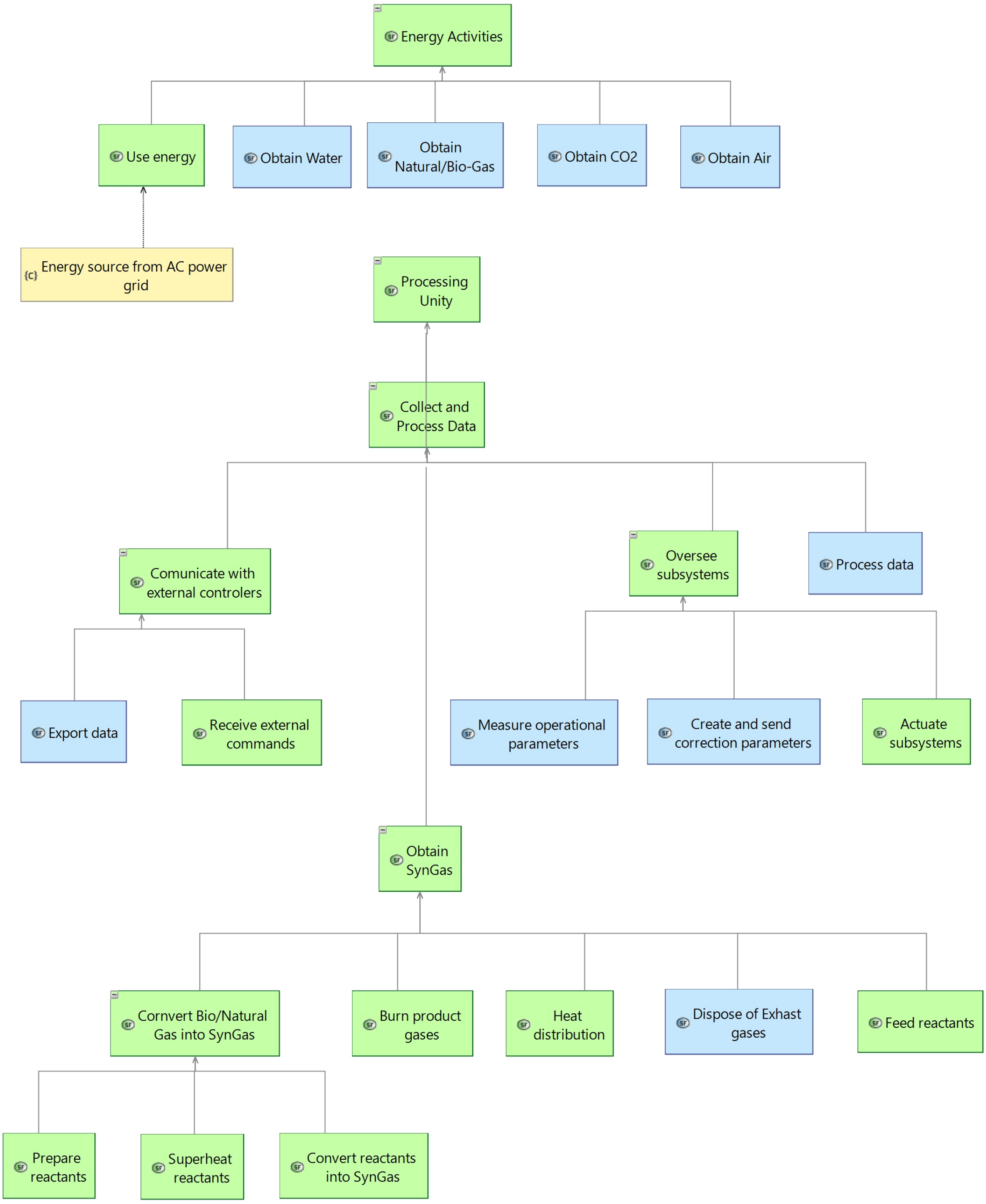
A FUNCTION DIAGRAMS

Figure 29 – OA - Root Operational Activities.



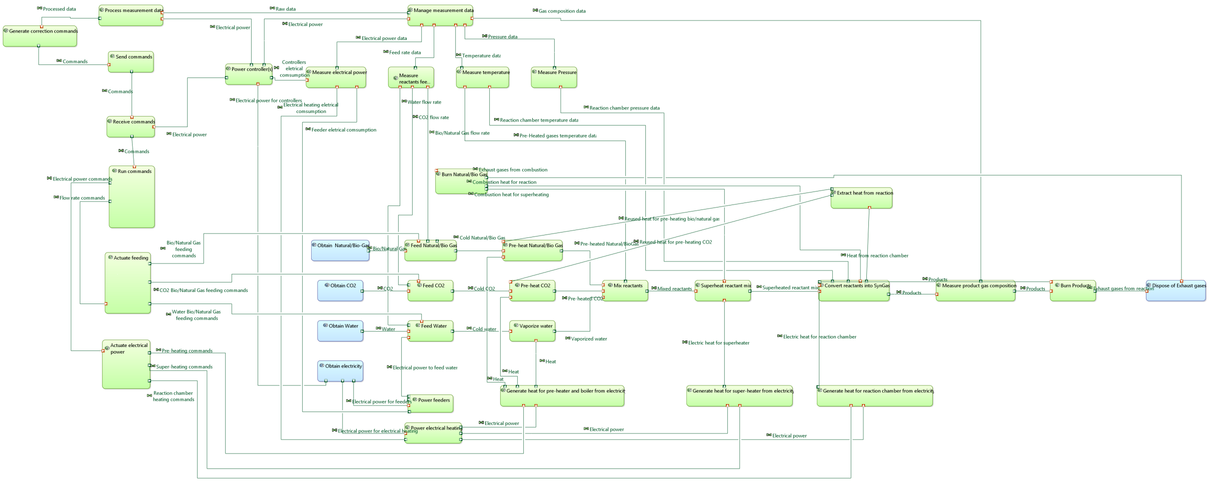
Source: Author

Figure 30 – SA - Root System Function Diagram.



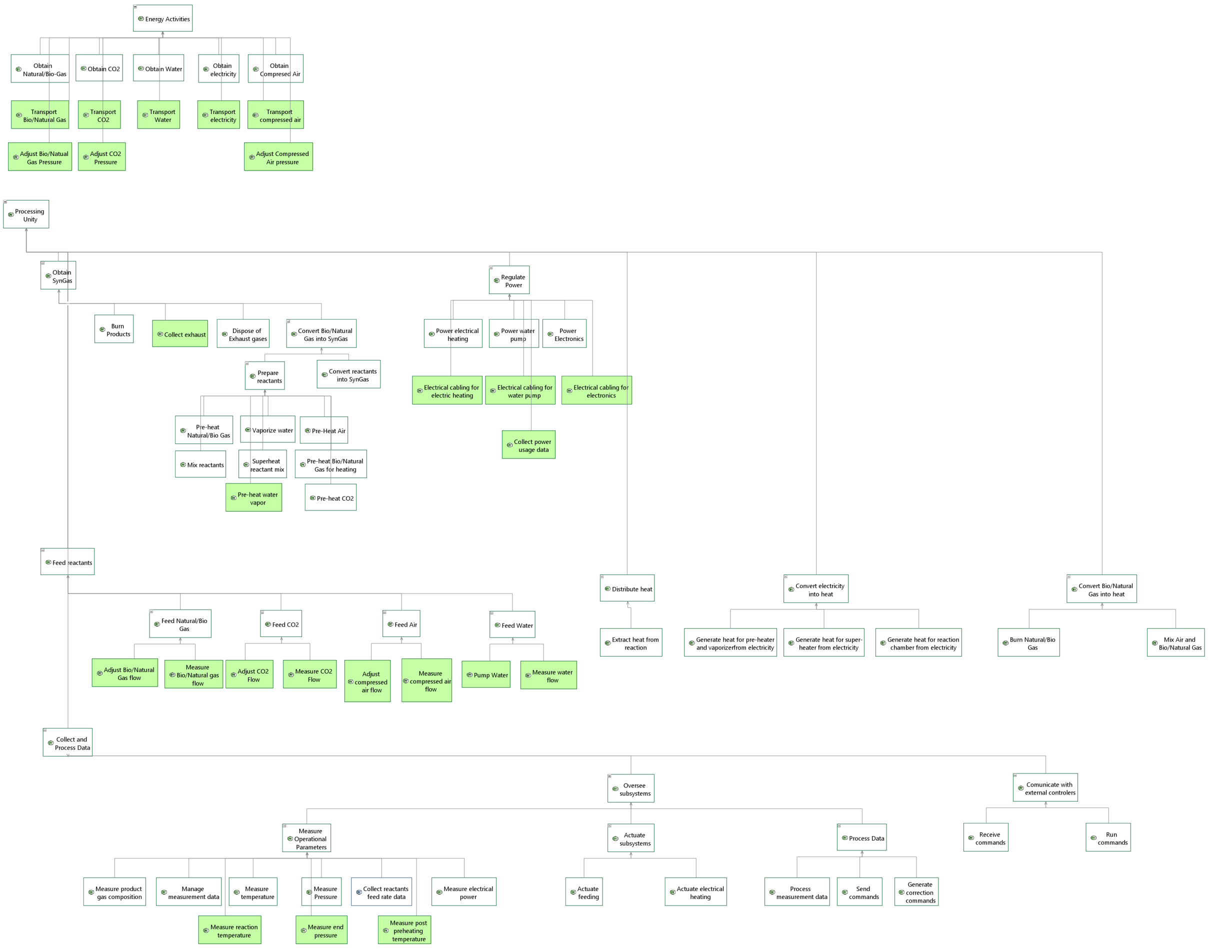
Source: Author

Figure 31 – LA - Root System Function Diagram.



Source: Author

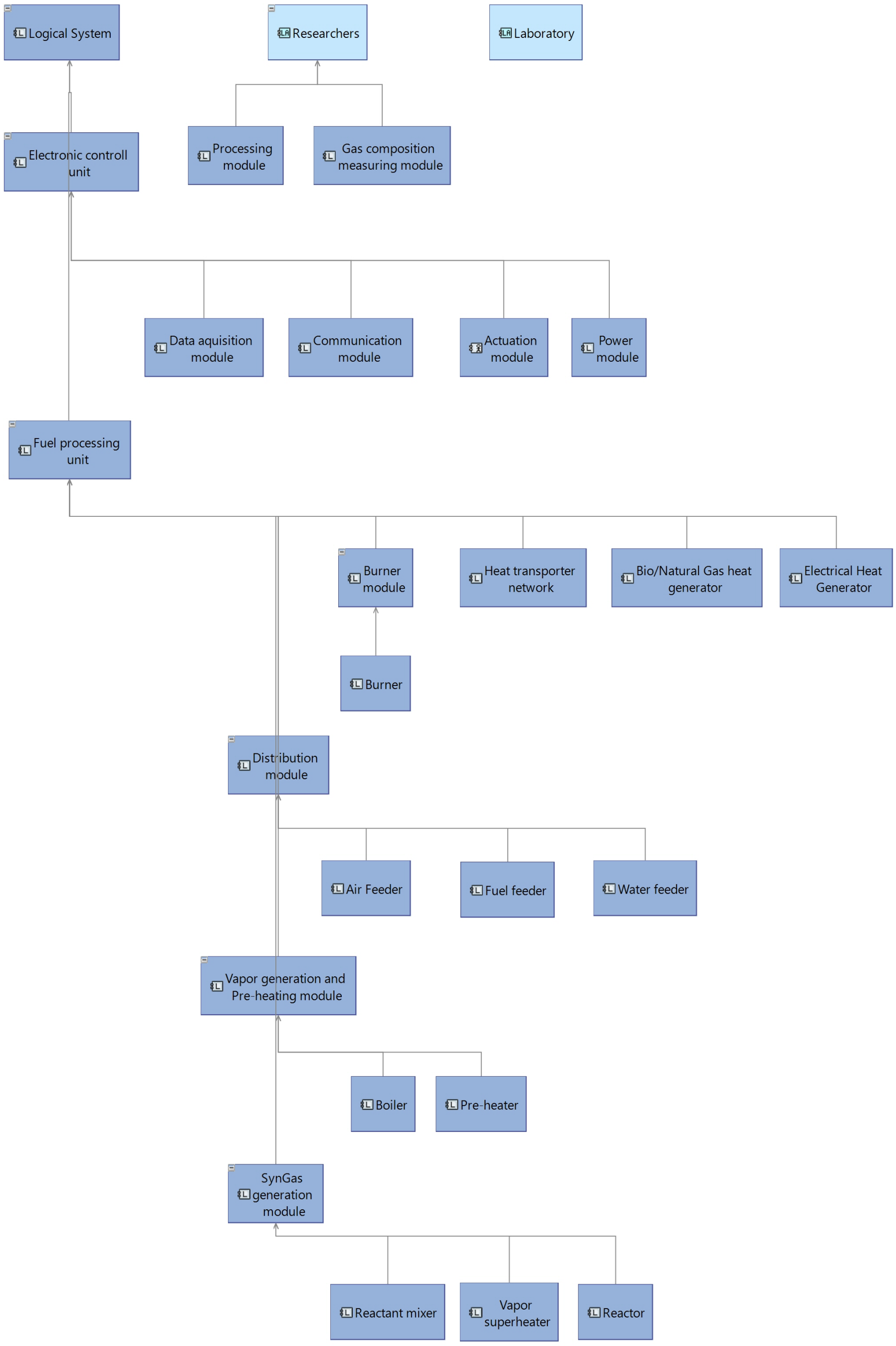
Figure 32 – PA - Physical Function Diagram.



Source: Author

B COMPONENT STRUCTURE DIAGRAMS

Figure 33 – LA - Component Structure Diagram.

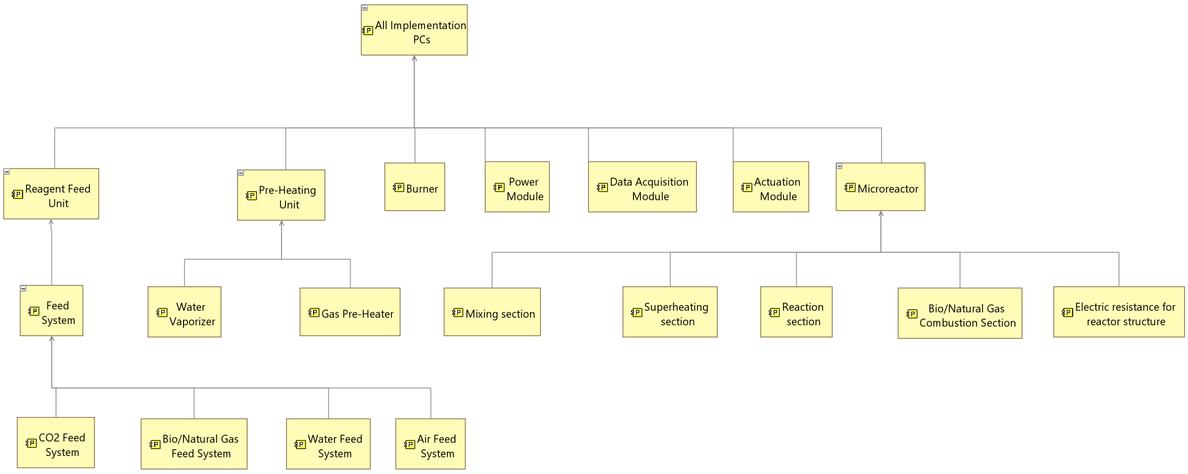


Source: Author

Figure 34 – PA - Behaviour Component Diagram.

Source: Author

Figure 35 – PA - Implementation Component Diagram.



Source: Author

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