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APPLICATION OF A DESIGN STRUCTURE MATRIX METHODOLOGY TO STEP PLASMA CONTROL SYSTEM DESIGN

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Abstract

Achieving reliable control of a burning plasma is a fundamental challenge for realizing a commercially viable fusion power plant. This requires a real-time, closed-loop plasma control system (PCS) capable of sensing plasma states, processing control solutions, and actuating responses under stringent performance constraints. The complexity of plasma physics and the strong interdependencies between sensors, actuators, and control algorithms demand a structured, systems-engineering driven approach.

This paper introduces a methodology that integrates Design Structure Matrix (DSM) techniques with Model-Based Systems Engineering (MBSE) to manage these complexities. The DSM provides a compact representation of dependencies among actuators, sensors, physical processes, and requirements, enabling automated consistency checks, clustering, and visualization. A provisional DSM for the STEP prototype reactor (SPR) is presented, demonstrating how clustering decomposes the PCS into relatively independent subproblems, supporting modular design, parallel development, and early identification of critical interfaces.

The approach enhances traceability, reduces integration risks, and informs sensor selection and control architecture definition. Future work includes extending the model to incorporate dynamic operational scenarios, linking to simulation models for quantitative analysis, and progressing toward a digital twin framework to enable automated verification and lifecycle integration.

1. INTRODUCTION

Control of a burning plasma is a defining challenge for the creation of a viable fusion power plant. Achieving this necessitates delivery of a reliable real-time, closed-loop plasma control system capable of sensing the state of the plasma, processing information to determine a plasma control solution, and implementing this via appropriate actuators. Fusion plasmas are highly complex physical systems, meaning the interfaces between the different system elements (i.e., physical processes in the plasma, diagnostics systems, controllers, and actuators) are highly interdependent.

Hence, a robust systems engineering approach is required to manage complexity from design through to operations. This is achieved through a design structure matrix (DSM) approach applied in combination with established model based systems engineering (MBSE) methods. This approach provides a robust mapping of the interactions between different system elements, allowing key dependencies to be identified and managed early in the development process. Hence, DSM facilitates better planning, reduces costly iteration loops, and enables parallel work on loosely coupled modules. Additionally, it assists in revealing hidden connections, ensuring that no critical design relationships are overlooked.

An initial DSM model for the STEP prototype reactor (SPR) defining the critical dependencies between plasma processes and actuators is presented. This serves as a basis for the definition of the physics models necessary to reconstruct key parameters from measured data while providing early performance estimates for individual sensors and models (including accuracy, precision, time resolution, and measurement range). It also facilitates the identification of critical sensor systems and the definition of subsystems within the control system architecture. Areas of future work, building on the information presented here, are also outlined. This serves as a robust foundation for iterative refinement as the STEP tokamak design matures, ensuring maximum benefits from a model-driven approach.

2. OVERVIEW OF THE METHODOLOGY

2.1. Design Structure Matrix (DSM)

A Design Structure Matrix (DSM) is a compact and systematic representation of interdependencies within complex systems [1]. It is structured as a square matrix where each row and column corresponds to a system element, and off-diagonal entries indicate dependencies between elements. These dependencies can encode different types of information in various modalities including binary values to denote the presence or absence of a dependency, scalar values to quantify the strength of the dependency, or colour coding to classify dependency types or characteristics.

DSM variants exist for different domains, including technical, organizational, and temporal systems [1]. In systems engineering, the product DSM is widely applied, where rows and columns represent technical components, and off-diagonal marks denote interfaces. This representation supports integrative activities such as change management, risk management, requirements management, and interface management. For instance, a DSM can effectively capture the interconnections within a nuclear fusion diagnostic system, enabling engineers to visualize and manage complex interface relationships.

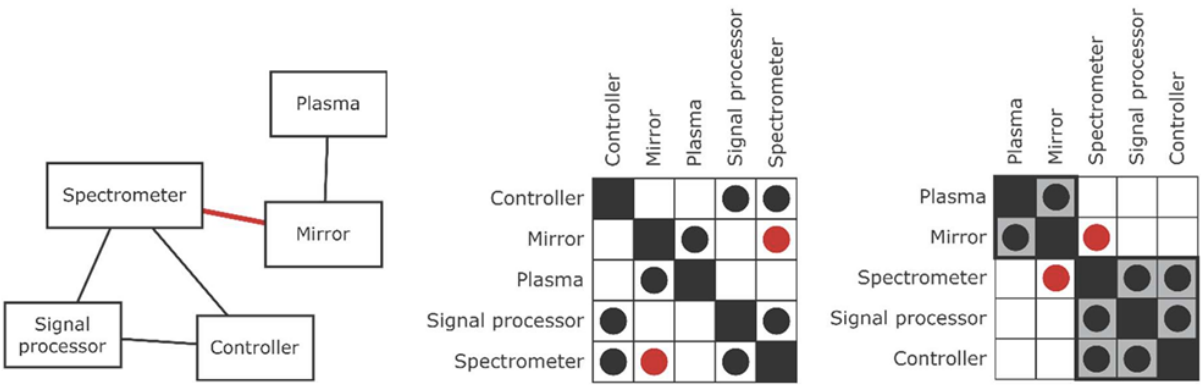

*Figure 1 - **Left:** A diagnostic system as a network of interdependent components. **Centre:** A DSM representation of the system maps dependencies as off-diagonal marks. **Right:** A clustered matrix.* [2]

One of the key advantages of DSM is its ability to reveal modular structures within a system. This is achieved by clustering, grouping elements with strong internal dependencies into modules, while minimizing external dependencies between modules (as illustrated in Figure 1). This modularisation is critical for enabling parallel development, reducing costly iteration loops, and improving overall system robustness. While small DSMs can be clustered manually, large-scale systems typically require automated clustering algorithms to identify optimal modular configurations.

DSM construction often uncovers hidden dependencies or missing elements that are not apparent in conventional system descriptions. This capability makes DSM a valuable tool for the analysis of complex systems, allowing stakeholders from diverse disciplines to engage in system analysis without requiring deep technical expertise. In the context of plasma control systems, DSMs can map dependencies among actuators, sensors, and physical processes, providing insights that inform control strategies and integration planning [3]. By identifying critical interactions early in the design process, DSM facilitates better planning, reduces integration risks, and ensures that no essential relationships are overlooked.

Application of DSM supports application of traditional Model-Based Systems Engineering (MBSE) techniques. MBSE enables a structured approach to managing complex design information by replacing traditional document-based methods with a centralized system model. Unlike documents, which often contain overlapping and loosely linked information, MBSE organizes data into functional, behavioural, and structural architectures within a single repository. DSM serves as a practical method to visualise, analyse and verify MBSE data.

This overall approach improves traceability, consistency, and communication while reducing errors caused by uncontrolled interdependencies. The intention is that as the DSM inputs are developed further, they are derived directly from a central model ensuring they remain accurate and up to date.

2.2. Metamodel of the Plasma Control Problem

This work applies the DSM approach to model the interface architecture of the STEP plasma control system (PCS). The model captures key system elements, including physical plasma processes (e.g., D-T fusion, particle transport), sensors such as diagnostic systems, and actuators like TF/PF coils and fuel pellet injectors. The PCS model is based on a metamodel that defines six element types (outlined in Table 1) – these define the fundamental architecture of the plant DSM constructed for the STEP PCS. The full metamodel and an example instantiation are shown in Figure 2.

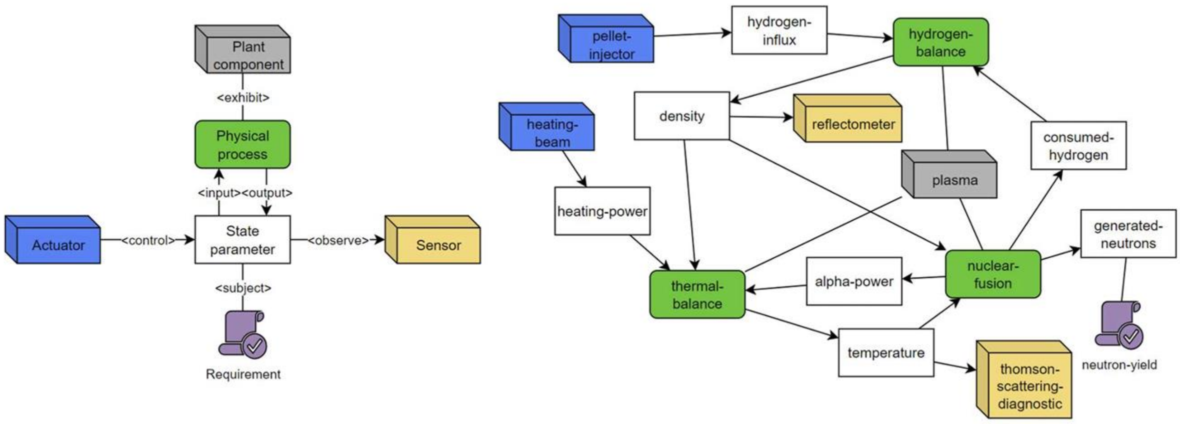

*Figure 2 – **Left**: Overview of the metamodel defining the element and dependency categories used to model the PCS. **Right**: An example instance of the metamodel covering a subset of the actual elements and dependencies of the STEP PCS.*

Interfaces and interdependencies between these elements are explicitly represented, enabling systematic analysis of the whole system. A sorting algorithm is then applied to cluster highly interdependent elements as outlined in Section 2.1 above, with provision for manual fine tuning where needed. This clustering process supports grouping of the applicable physical interactions including interfaces between the actuators and applicable physical processes in the plasma, sensors and the target measurement parameters, self-interactions within the plasma and interactions between the plasma and tokamak components such as the first wall.

Table 1 - Definition of element types used in the DSM metamodel.

Element	Overview
Plant Components	*A physical object of the system under control e.g., first wall and divertor tiles. This is also used to define the plasma itself.*
Physical Processes	*A physical phenomenon that governs the behaviour exhibited by a plant component e.g., D-T fusion, particle transport or wall heating.*
Actuators	*A device whose output can be controlled in real-time e.g., TF/PF coils or fuel pellet injectors.*
Sensors	*A device whose input can be observed in real-time e.g., magnetic pick-up coils or bolometers.*
State Parameters	*A quantifiable aspect of the plant that indicates its state e.g., plasma electron density or alpha heating power.*
Requirement.	*A statement expressing a desired value, range or trajectory of a state parameter.*

2.3. Technical Implementation

Managing the data underpinning a DSM model can be achieved using a variety of methods. For complex data, purpose built systems modelling tools (such as SysML or Capella) are preferred over basic diagram editors to minimise risk of missing dependencies and allow export of the data in a practical format. In this instance the underlying model was defined using the Elephant Specification Language (*ESL*) and parsed using the open source python package (*RaESL*). ESL is a formal, text-based language for specifying engineered systems [4]. The language enables the definition of multi-level architectures, interfaces, functions, requirements, and relationships using structured syntax and semantics.

This formalization allows system specifications to be parsed and transformed into graph models, to which DSM techniques can be applied. This workflow provides an end-to-end process for building, validating, and visualizing system models. A modular architecture, allowing different datasets and implementations of the clustering process to be configured for specific purposes. Configuration files (in *.json* format) allow for custom DSM organization. This implementation uses Jupyter notebooks as the front end for running workflows allowing for export of full DSM models in image, HTML, or spreadsheets formats.

3. APPLICATION IN THE STEP PROGRAMME

3.1. Underpinning Data

The model of the STEP PCS was constructed using provisional information gathered from UKAEA design documentation and expert discussions, with assumptions validated by stakeholders where necessary. The model encompasses four main categories:

- **Actuators** – The definition of these are relatively mature, with 15 elements included in the model, covering technologies such as TF/PF coils and heating systems.
- **Sensors** - Sensor selection remains under development; therefore, a comprehensive set of 30 candidate sensors was modelled to maintain flexibility.
- **Plasma Processes** - Physical processes and state parameters which describe the plasma. These were sourced from a proprietary dataset generated by the Dutch Institute for Fundamental Energy Research [3].
- **Measurement Parameters** – These define the functional requirements for sensing without prescribing specific technologies, supporting solution-independent design. These parameters enable alternative sensing approaches to infer critical plant states through different intermediate measurements.

It should be noted that, given the early stage of the STEP concept at the time this work was completed, this data should not be seen as definitive. Rather this serves as a baseline dataset for construction of an initial DSM (presented in 3.2 below) which can then be iterated upon as the STEP design matures, and more accurate data becomes available from technology development and qualification activities.

3.2. DSM for the STEP Plasma Control System

This data was used to construct a plant DSM for the STEP PCS model based on the elements listed in Table 2. These elements were clustered into functional groups (as described in Section 2) to analyse the underlying structure of the data. The full DSM, with all functional groups labelled, is shown below in Figure 3:

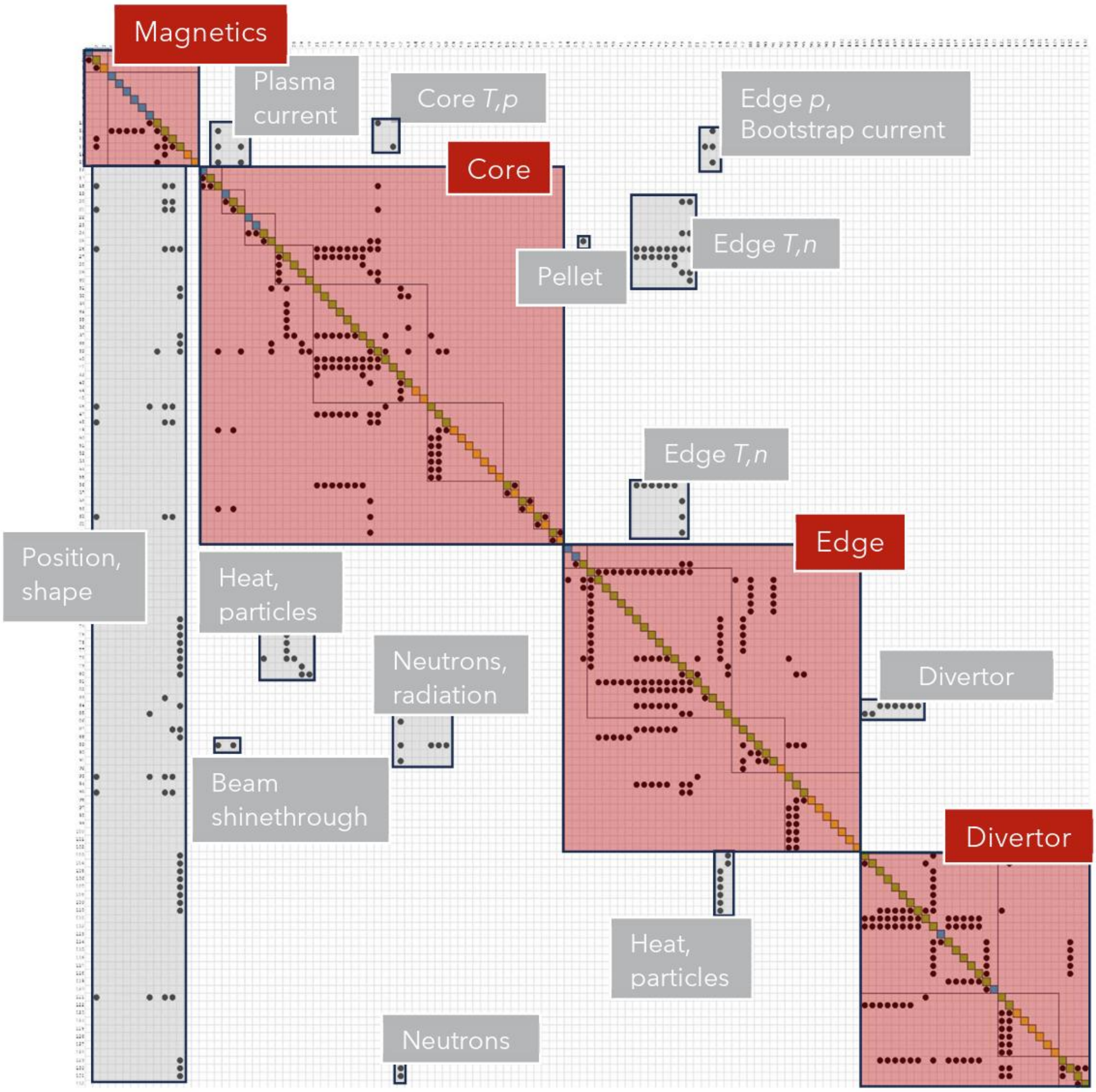

Figure 3 – Plant DSM for the STEP PCS with functional groups labelled.

Four primary clusters were identified - magnetics, core, edge (including plasma-wall interactions), and divertor (including divertor targets). These clusters align with major plasma regions and functions such as heating and fuelling in the core, radiative cooling and transport in the edge, and detachment and exhaust processes in the divertor. The remaining inter-cluster dependencies are minimal, typically covering a small set of well-characterized physical phenomena such as plasma current, neutron interactions, bootstrap current and pellet injection.

3.3. Application to Control Architecture Definition

This decomposition process can be used to the development of the PCS by breaking down the complexity of full system. This provides a framework for the design process to be approached per cluster - bounds and reference profiles can be specified for the variables within a cluster, simulation models for the associated physical processes generated, and actuators and sensors that interact with the processes can be specified. These elements are integrated, analysed and verified on a cluster level, not system wide.

This process allows the PCS specification to be decomposed into subproblems and their interactions. A dedicated viewpoint then compiles subsets of the full specification for each subproblem, ensuring completeness and consistency by generating these views directly from the DSM model rather than manually authoring documents. Each subproblem specification includes actuators, control variables, physical processes, and associated interactions, with linked requirements automatically inserted as subclauses.

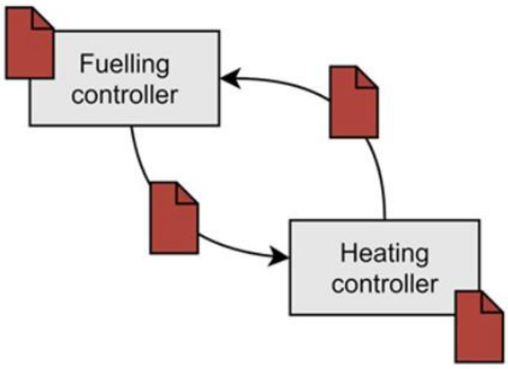

Figure 4 – Illustration of how a specification can be generated for each control subproblem and each interaction.

Additional viewpoints can generate interface specifications for pairs of subproblems by listing shared variables and related requirements, though most will be empty due to clustering. These generated views are intended to support communication between the PCS architect and subsystem designers, clarifying responsibilities and interaction agreements. If subsystem teams adopt model-based methods, these specifications can also be exported as raw data for direct integration into their design tools, enabling a more automated and traceable workflow.

4. DISCUSSION AND FUTURE WORK

This work establishes a framework for the integrated development of the STEP PCS by combining DSM and MBSE techniques. The PCS is represented as a network of actuators, sensors, physical processes, parameters, and requirements, stored in a formal data model. This model enables automated dependency analysis, consistency checks, and visualization as a plant DSM. The DSM view is particularly valuable for mapping the complete PCS structure and decomposing it into relatively independent subproblems.

It should be noted that the data serving at the basis of this model in its current iteration is not expected to be a definitive representation of the STEP plasma control model. This is due to the relative immaturity of the STEP design at the time this work was delivered and the inherent uncertainties in the delivery of a first-of-a-kind plant. However, there is clear value in applying this process early in the design of the PCS to minimise complexity in the development process, inform planning activities, scope R&D and support integration with broader MBSE activities employed in the STEP design. Ultimately, the intention is that this work forms the basis for an iterative design process which enables an efficient delivery of the PCS within the STEP programme.

Supporting this aim, several future directions have been identified:

- **Measurement Systems -** For measurement systems, the current model captures only the physical sensors and their interactions with plant components. However, real measurement architectures also include software observers that process raw sensor data into meaningful parameters, often using physics-based models. These observers can share data, creating interdependent networks with multiple pathways for deriving the same parameter. A model-based approach for such architectures has been demonstrated in prior work, enabling simulation of performance attributes like accuracy and latency. Extending the PCS model in this direction would allow designers to optimise measurement architectures and propagate requirements to subsystems, while supporting cost and risk assessments.

- **Operational Scenarios** - These scenarios define time-dependent trajectories for plasma parameters across different pulse phases. While the current model supports static requirements, the same framework can incorporate dynamic requirements linked to scenario definitions. By embedding these scenarios into the DSM model, consistency checks can be automated, and validated scenarios can feed directly into control specifications. This integration would strengthen traceability between high-level operational goals and control system design.

- **Simulation Models** - Linking the DSM model to simulation models would bridge the gap between qualitative system descriptions and quantitative analysis. By associating physical processes with mathematical models, the DSM can identify coverage gaps and organize models for integrated simulations. This capability would support both fast, low-fidelity simulations for controller design and high-fidelity models for verification. Automating the selection and integration of these models into the control design process would further enhance the utility of the MBSE framework.

- **Discrete Events and States** - These are critical for managing transitions between operational regimes and responding to unplanned disruptions. This requires defining supervisory control logic capable of detecting events and switching control modes in real time. Tools like CIF4, which formalize plant behaviour as state machines and support automated code generation, could be integrated into the MBSE workflow. Doing so will require metamodel extensions to include states and events, enabling conditional relationships across requirements, models, and trajectories.

- **Control Synthesis** - While current workflows rely on human interpretation of specifications, the formal nature of MBSE data opens the door to automated controller generation. Coupled with simulation models, this approach could enable automated analysis and verification, reducing design time and improving consistency. Human oversight will remain essential for interpreting results and refining system-level decisions, but automating lower-level implementation will accelerate iteration and maintain quality.

- **Digital Twin Development** - A comprehensive, self-consistent representation of the system that integrates requirements, interfaces, simulation models, and lifecycle data. This digital twin would serve as a central reference for stakeholders, supporting collaboration and decision-making. While achieving this vision poses technical and organizational challenges, it offers significant benefits for traceability, risk reduction, and overall project performance.

5. CONCLUSIONS

This work presents a framework for the integrated development of the PCS using a combination of DSM and MBSE techniques. This includes a DSM-based visualization of a provisional dataset (covering actuators, sensors, physical processes, parameters and requirements) for the STEP PCS and a decomposition into relatively independent subproblems to support control architecture definition. This information is stored as a data model allowing it to be managed and analysed with the help of a software toolbox.

A key outcome of this work is the successful demonstration of the DSM methodology to the development of a complex PCS system, including application to the definition of the control architecture. This serves as a basis for the application for this methodology to manage the design of the STEP plasma control system (including the supporting R&D and broader systems integration) as the programme develops. An overview of the specific technical challenges and applications which these methods can be applied to is also presented, intended to serve as a basis for future work in this area.

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REFERENCES

[1] Eppinger, S. D., & Browning, T. R., "Design Structure Matrix Methods and Applications," MIT Press, 2012.

[2] Beernaert, T., Verlaan, A., Bock, M. D., Moser, L., Etman, L. F., Classen, I. G., & Baar, M. R., "Multi-Level Architecture Modelling and Analysis: The Case for Model-Based Systems Engineering of Fusion Diagnostics," *Fusion Engineering and Design,* p. 114571, 2024.

[3] Beernaert, T., Baar, M. D., Etman, L., Classen, I., & Bock, M. D., "Managing the Complexity of Plasma Physics in Control Systems Engineering," *Fusion Engineering and Design,* p. 114436, 2024.

[4] Wilschut, T., Hofkamp, A. T., Schuijbroek, T. J., Etman, L. P., & Rooda, J. E., "Bridging the Gap between Requirements Engineering and Systems Architecting: The Elephant Specification Language," Design Science, 2024.