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

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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 complex and highly interdependent. A robust, systems engineering led approach is required to manage this complexity from design through to operations.

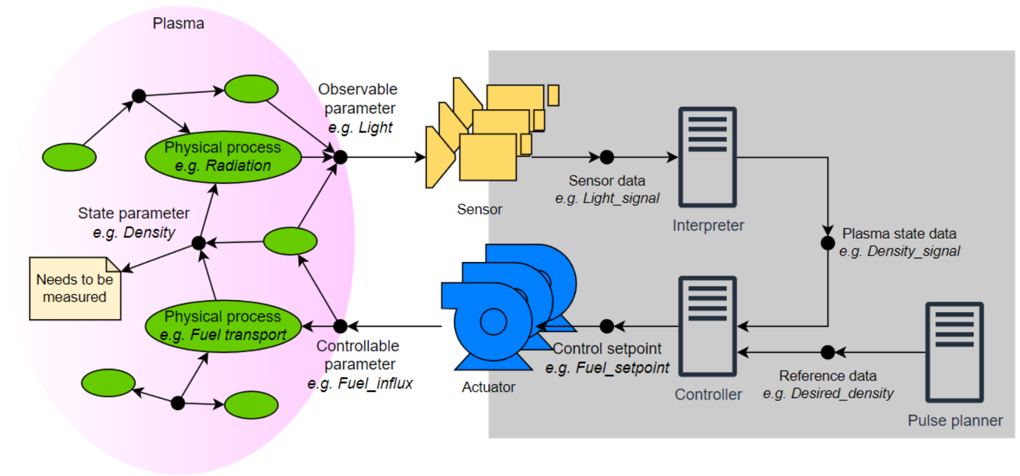

Figure 1 – High level overview of the model structure illustrating the core elements of the plasma control system (including the relevant plasma processes, sensors, controllers and actuators).

This can be achieved through use of a design structure matrix (DSM) approach[1]. A DSM is a compact, matrix-based representation of the interrelationships and dependencies among elements in a complex system. 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.

2. RESULTS

An implementation of the DSM approach to the design of the STEP plasma control system – specifically an interface model of the plasma control system (outlined in Figure 1) – is presented here. This model covers key system elements of the plasma control process, defined to include physical plasma processes (e.g., D-T fusion, electron transport etc.), sensors (i.e., plasma diagnostics systems) and plasma control actuators (e.g., TF/PF coils, fuel pellet injectors etc.). Key interfaces between these elements – including interdependencies between plasma processes and interfaces between sensors and actuators – are also modelled. Once the core system elements are modelled, a sorting algorithm is applied to group elements of the system. This process systematically groups elements of the systems which are highly interdependent such that the elements within them are minimally interdependent with those in other groups. An outline of this process for a simplified dataset is illustrated in Figure 2. This allows for clear identification of sub-groups with highest interdependency, simplifying the management of complex systems.

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[1] *T.F. Beernaert, M.R. de Baar, L.F.P. Etman, I.G.J. Classen, M. de Bock (2024).* Managing the Complexity of Plasma Physics in Control Systems Engineering. *Fusion Engineering and Design*, 203, Article 114436. https://doi.org/10.1016/j.fusengdes.2024.114436

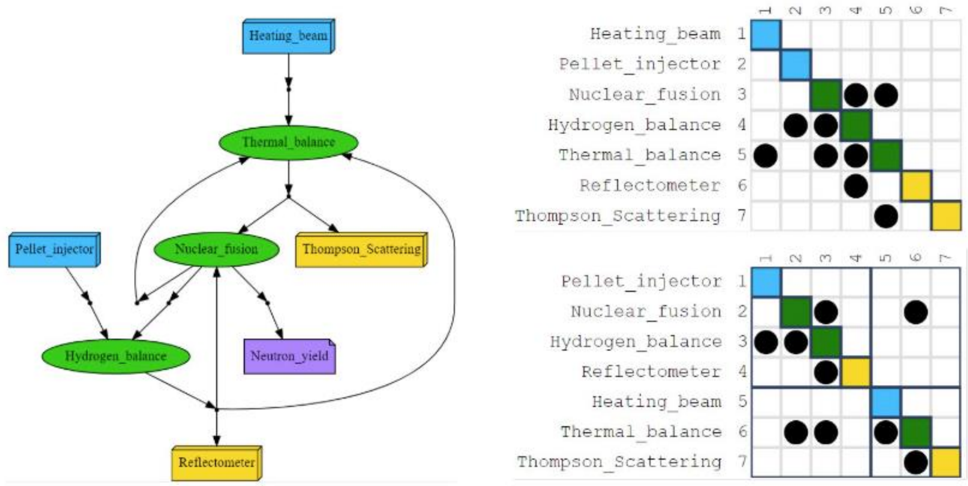

Figure 2 – Illustration of the sorting algorithm as applied to a simplified data set (shown in graph form on the left) expressed in DSM matrix form before and after the sorting process (top right and bottom right respectively).

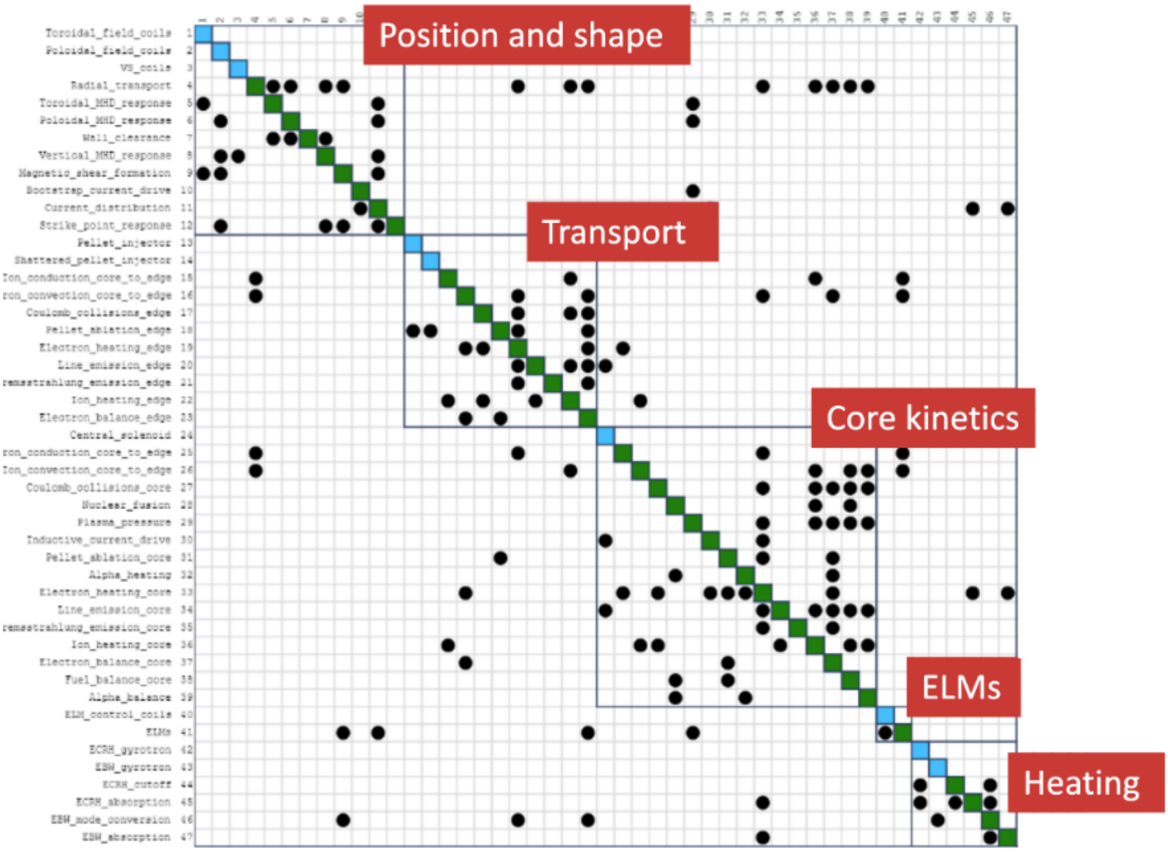

Figure 3 – DSM Matrix showing key dependencies between plasma processes and actuators (illustrated with green and blue squares respectively) for the STEP tokamak and the identified independent subgroups (labeled in red).

An initial dataset for the STEP prototype reactor (SPR) defining the critical dependencies between plasma processes and actuators is presented, structured within a DSM matrix (a subset of which is shown in Figure 3). This data 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. This serves as a robust foundation for iterative refinement as the STEP tokamak design matures, ensuring maximum benefits from an MBSE-driven approach. Moving forward, this model will guide R&D efforts on essential sensor technologies, optimise sensor selection for the STEP SPR, and mitigate unforeseen design impacts on the plasma control system.