From Physics to Project Management: A Multi-Domain Matrix Model for the Distributed Analysis of Nuclear Fusion Systems

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Abstract: Nuclear fusion reactors operate in extreme and complex physical regimes. Predicting the behavior of these systems is essential for verification and validation, but requires the integration of diverse analysis activities, constrained by domains such as cost and human resources or availability of analysis tools. In this paper, we explore the use of a Multi-Domain Matrix (MDM) to formalize cross-domain aspects in the planning and coordination of such complex analysis campaigns. We represent the engineered system as a matrix of physical effects and the analysis campaign as matrix of activities. From the mapping between these domains, we can identify missing aspects, prioritize activities and derive which critical assumptions. Sequencing the model improves the planning. We apply the proposed method to a diagnostic shutter, a common subsystem in next-generation nuclear fusion reactors. The MDM successfully supports planning of multiple analysis activities, and suggests that it can be expanded to more domains.

Keywords: Multi-Domain Matrix, Systems Engineering, Nuclear Fusion, Project Management, Complexity

1 Introduction

One of the biggest challenges in nuclear fusion systems engineering is to design systems that remain functional in a complex and extreme physical environment. The effects of high thermal fluxes, neutron bombardments, exotic particles, strong magnetic fields and an ultra-high vacuum need to be accurately predicted before installing a new subsystem in a fusion reactor. Analyzing these effects in isolation is not sufficient - we need to understand *emergent* behavior.

The analysis of nuclear fusion systems brings about some problems. Firstly, there simply do not exist test set-ups that can replicate the extreme physical loads in a nuclear fusion reactor at a large scale. Understanding the degradation of material and component properties throughout the reactor operational lifetime is a key issue to allow the design, the licensing, and the reliable operation of these facilities. Additionally, the requirements for future fusion technology will vary significantly from machine to machine. For example, the neutron fluxes in demonstration reactor DEMO will be orders of magnitude larger than in test reactor ITER, and dynamic fluxes due to plasma instabilities are likely to set those design requirements.

There are only a few facilities with the aim to test and verify the various aspects associated with these fluxes. The Magnum facilities in the NWO institute DIFFER provides the steady-state thermal and plasma fluxes at the materials or subassembly scale and can simulate dynamic fluxes due to Edge Localized Modes (ELMs). The facilities of the Kharkiv Institute of Physics and Technology comprise a QSPA Kh-50 quasi-stationary plasma accelerator and a magneto-plasma compressor. These can replicate energy flux densities in the range of 1-25 MW/m2, particle fluxes up to 1026-1029 ion/m^2/s, plasma stream velocities up to about 500 km/s and pulse durations in the range of 1-250 µs. IFMIF-DONES will be the world facility to generate the (highly energetic) 14.1 MeV fusion relevant neutrons.

These machines are intended for small-scale material research, unsuitable for component or system-level tests. Additionally, there are no test facilities that can explore the synergetic effects of the extreme loads. This makes it difficult to accurately predict how combinations of physical effects drive the behavior of the system.

As a consequence, the system is analyzed in multiple distributed activities. However, decomposing the analysis campaign inadvertently requires assumptions on the results of some of these activities. Another challenge is the budgeting of monetary, knowledge and human resources, as well as the availability of test set-ups or numerical simulation models. When planning an ensemble of activities, system architects and project managers are constantly asking the following questions:

1. Will our plan cover all foreseeable physical effects? What effects of the system are we not testing?
2. What is the order in which we should execute analysis activities?
3. What assumptions are we implicitly making by decomposing the analysis process in separate activities?

These three questions are the main drivers of our work. Dependency Structure Models (DSMs) have proven to be valuable to gain an oversight on complex matters, to identify mismatches, and to plan sets of coupled activities. However, there has been little emphasis on modelling complex physical effects.

In this paper, we present a newly developed DSM-based technique to support systems engineers in planning multidisciplinary analysis activities, accounting explicitly for complex physical effects. In the next section, we will visit relevant literature on engineering design, physical systems and DSMs. Section 3 clarifies terminology, proposes our method and introduces a Multi-Domain Matrix (MDM) as a central view on the problem. In Section 4, we apply the method to the development of a shutter subsystem that will support an optical diagnostic system in ITER. This demonstration shows how the method can successfully identify gaps, improve scheduling, and minimize the impact of analysis assumptions on rework.

2 Background

DSMs support the integrated management of various activities in the systems engineering lifecycle (Eppinger et al., 2014). Functional system architectures have received much attention, i.e. models of the *desired* couplings between system elements and their *desired* behavior (Wilschut et al., 2018; Drave et al. 2020). But in a complex physical environment, designers have to deal with many *undesired* couplings and need to reason about *undesired* behavior. It is in the designers' best interest to design for robustness, i.e. limiting the impact of undesired effects on functionality (Mathias et al., 2011).

Physical effects (sometimes 'physical processes' or 'phenomena') follow from the laws of physics that govern the time-evolution of a system's state (Borst et al, 1995; Yoshioka et al., 2004). These works represent a physical state by a set of physical parameters and express a physical effect as a relation between two or more parameters. A physical effect can be modelled numerically, and observed and tested in real-life. Two effects that influence and depend on the same parameter are said to be *coupled,* thus creating a physical effect network (Ramsaier et al., 2020). This paradigm has made its way into the parameter diagram of SysML, the most popular language for systems modelling (Drave et al. 2020). Figure 1 illustrates a network of parameters and effects, and two orthogonal DSM views.

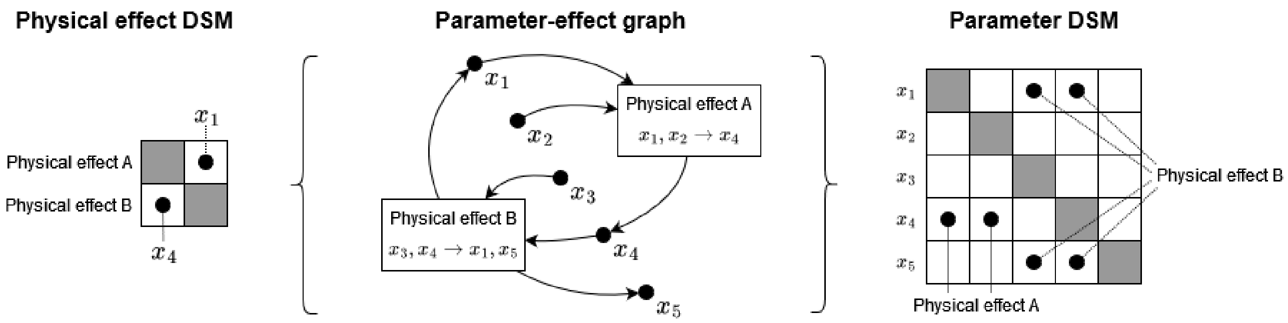

Figure 1. The behavior of physical systems can be represented as a graph of parameters and physical effects (center). This network can be projected on a DSM of physical effects (left) or parameters (right).

Parameter DSMs are common throughout literature (Browning, 2016), but physical effects DSM are almost exclusively used by Multi-Disciplinary Analysis and Optimization (MDAO) (Lambe and Martins, 2013; Rogers et al., 1998). In this context, Lambe and Martins (2013) introduce the XDSM, a network of mathematical models augmented with a coordination scheme, i.e. a sequence of execution. The XDSM seems fit for our purpose, were it not for a few limitations.

Firstly, we need to integrate architecture. Merely identifying any undesired physical behavior in an architecture candidate can already provide valuable feedback to change the layout or technology of certain elements. Secondly, the XDSM is intended for mathematical models. Although developing such models is an ongoing effort in nuclear fusion (Sinha et al., 2021), detailed simulations of first-of-a-kind systems are generally less available. Highly multidisciplinary systems are often analyzed by a combination of numerical models and hardware tests (Braspenning et al., 2008). Our representation needs a higher abstraction level, independent from the actual analysis techniques. Finally, we need to capture other domains of multidisciplinary systems analysis, such as knowledge disciplines, physical prototypes, analysis tools, and people. Such heterogeneous information is better organized in a Multi-Domain Matrix (MDM) (Maurer and Lindemann, 2008), an arrangement of multiple DSMs and the mappings between them.

We can conclude that DSMs are excellent tools to manage complex dependencies in engineered systems, including distributed analysis campaigns. Nevertheless, for our purposes regarding first-of-a-kind systems, such models must represent complex physical behavior at a sufficiently high level of abstraction. This is exactly the gap we address in the remainder of this paper: To develop a DSM technique that (1) formalizes the physical behavior of multidisciplinary high-tech systems on an abstract level and (2) that can integrate the various domains of distributed analysis activities.

3 Method

Let us begin by introducing a common perspective on the engineering development process and clarify important terms.

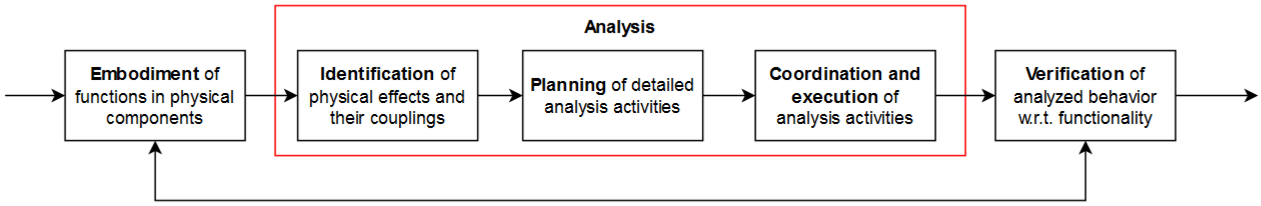

Figure 2. A simple representation of a design process. We focus on the analysis stage, which succeeds embodiment and precedes verification. Our modelling method supports this stage in the identification, planning and coordination steps.

Most development processes begin with the formulation of *function*. A function is a task or service that needs to be realized by a system in design. Subsequently, physical components are designed that should carry out (part of) those functions. This design process is called *embodiment*, *implementation* or *synthesis*. From the geometry and material of physical components, one can derive the *behavior* of the system through the act of *analysis.* Complex physical systems are typically analyzed from various disciplines that often correspond to branches of physics, such as mechanics or electronics. We refer to these processes as analysis *activities*. Finally, *verification* is the process of comparing the initially functions, expressed through requirements, with the behavior that results from analysis.

Our method further decomposes the analysis process in three steps:

1. **Identification**
   The first stage of the analysis process consists of identifying the physical effects that govern the behavior of the system. We declare these effects only on an abstract, domain-neutral level, in terms of input-output parameters. Physical effects are coupled if the output of one effect is the input of another.
2. **Planning**
   The second stage defines the activities that will analyze individual physical effects in detail. In this stage, resources have to be allocated to deal with questions such as: What knowledge or specialization is required? Who will carry out the activity? What hardware and/or software tools are needed? When will each activity be executed? How are they prioritized?
3. **Execution and coordination**
   The third stage executes the detailed analyses. Each analysis requires information as input, and returns analysis results. Some of these analysis results need to be shared between various analyses. Also unexpected changes from any domain, e.g. regarding budget, schedule, human resources or analysis tools, need to be responded to.

3.1 Multi-Domain Matrix

We propose an MDM model as a central overview for the different stakeholders throughout the above steps of the analysis process. A basic schematic of the MDM is shown in Figure 3. This schematic can be further extended with more domains, data and annotations, as we will see in the demonstration in Section 4. The remainder of this section explains how to construct, read and use the four regions I-IV of the model.

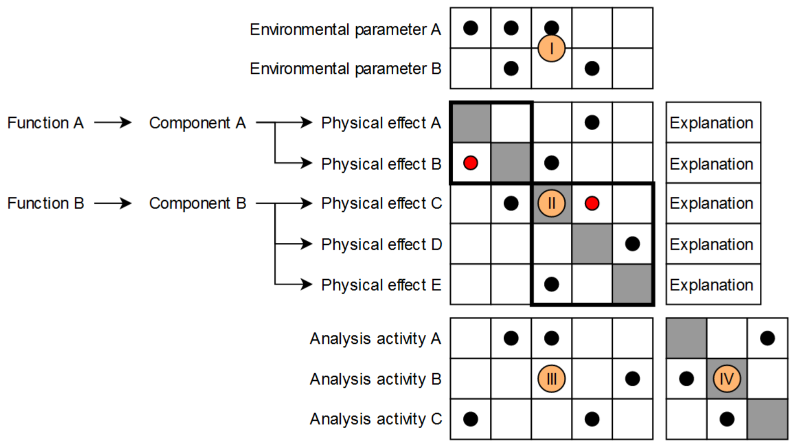

Figure 3. We propose a Multi-Domain Matrix (MDM) as an integrative view on the various aspects of the analysis process. The MDM comprises four submatrices I-IV.

In the center of the MDM, we find a DSM of physical effects (II). This is the matrix representation of a network of physical effects, such as on the right-hand side of Figure 1. It formalizes the physical behavior of the system on an abstract level. The matrix will be constructed in the analysis identification phase, right after the system's functions have been embodied in structural components.

We assign each physical effect to a single component. This assumption has some practical benefits: Primarily, since responsibility in collaborative engineering is often distributed along the lines of components, this assumption removes ambiguity about who is expected to analyze which effect. Secondly, a physical interaction between two components now is analogous to a dependency between physical effects, and can therefore be characterized by physical parameters. For example, components A and B have a physical interaction because effects A and B of component A are dependent on effects D and C of component B, respectively. In practice, there may be effects that unavoidably represent more than one component. We envision that such effects be suitably allocated to the aggregation of components, i.e. to the supersystem of components. However, such multi-level system perspectives are outside the scope of this paper.

The matrix can further be annotated with colors, numbers or text. For example, Figure 3 highlights some dependencies in red. These specific dependencies force designers to make critical assumptions on the behavior of the system. We will come back to these dependencies in Section 3.4. The table on the right of the matrix offers some space for an explanation per physical effect that could contain assumptions, risks, events or conditions that define the validity of these effects.

Matrix I above the physical effect DSM provide traceability between the system's physical behavior and its environment. Each of the listed parameters, such as temperature, pressure or magnetic field, represents an incoming physical flow over the system boundary, either from the environment or from an external system. Matrix I points specifically at those internal effects that are dependent on the environmental parameter. Matrices I and II are both constructed during the identification phase.

The bottom part of the MDM supports the subsequent planning phase. Matrix III has two functions. Firstly, it defines the detailed analysis activities that the team plans to execute in order to acquire a detailed description of the system's behavior. These activities can be a combination of hardware-based experiments and numerical simulations. Secondly, the mapping to the physical effects defines which physical effects should be investigated by which activity.

Finally, matrix IV captures information flows between activities. In our model, an information flow between two activities represents a detailed, quantitative description of one or more physical parameters. Such a description can be the result of one analysis, while it provides an input or boundary condition for another analysis.

The activity DSM will play an essential role in arranging and scheduling the flow of activities, and identifying which assumptions need to be made. Consider for example the following: a thermal analysis investigates how heat loads on a component result in a temperature distribution, and a mechanical analysis investigates how that temperature distribution leads to deformation. It is clear that the thermal analysis should be executed before the mechanical analysis, because detailed information about the temperature distribution should be passed from the former to the latter. However, if for some reason the mechanical analysis is carried out first, the analysist needs to make an assumption about the temperature. If the subsequent thermal analysis shows that the previously assumed temperature is too far off from the new analysis results, the mechanical analysis will have to be repeated.

We need to make assumptions whenever an upstream activity depends on information from a downstream activity. It is clear that such assumptions could lead to unexpected scheduling and cost overruns. For this reason, it is in everyone's best interest to minimize the amount of assumptions by strategically identifying information flows and prioritizing analysis activities in an early phase. This will be the topic of Section 3.3.

There are numerous other domains that influence our planning activities, e.g. people, knowledge and analysis tools. For now, the matrix in Figure 3 is the most basic representation that will help us coordinate the analysis activities. Adding more domains will be a direction for future developments.

The MDM supports all stakeholders in communicating and formalizing the analysis campaign, and particularly deals with our three research questions. In the following sections, we show how our model answers these questions one by one.

3.2 Does the analysis plan cover every foreseeable aspect?

This question is answered by inspecting the mapping matrix (III) from physical effects to analysis activities, column by column. A single mark tells us that the concerned effect is object of a single analysis activity. Multiple marks in the same column imply redundancy: The effect is covered in multiple analyses and results can be cross-checked. Most crucially, empty columns highlight risk: An effect that is not analyzed at all. Note that this view only captures a first-order check of the processes that were identified in the first step and does not account for the accuracy or rigor of the analysis plan.

3.3 How should we prioritize analysis activities?

We want to find an ordered flow of activities with a minimum amount of assumptions. An ordered flow ranks the activities in the DSM IV from top to bottom, where higher activities should be carried out before lower ones. Information flows below the diagonal will naturally follow this sequence, but information flows above the diagonal imply a feedback loop and will require an assumption. We prioritize activities by first identifying information flows, and then sequencing activities.

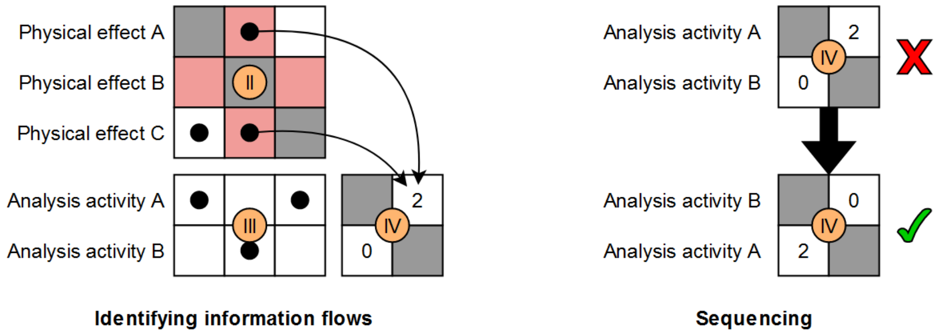

Figure 4. Left: Information flows between analysis activities can be derived from couplings between physical effects. Right: Sequencing the activity DSM leads to an ordering with a minimum amount of information flows above the diagonal.

We can systematically identify the required information flows between any two activities, by inspecting matrices II and III. We collect from matrix III the set of physical effects that is analyzed by each activity. In Figure 4, activity A analyses effects A and C, and activity B analyses effect B. Now matrix II will show if there are couplings between these two sets. These could occur on the squares marked in red. Here we find two couplings that point *from* the effects of activity B *to* the effects in activity A. This signifies that there are two information flows from activity B to activity A. We enter this number in the corresponding cell in the activity DSM, matrix IV.

The inferred activity DSM can now be ordered. The objective is to find a sequence of activities that minimizes the amount of dependencies above the diagonal. We will demonstrate this step in more detail in Section 4.2.

3.4 What assumptions do we have to make?

The optimal sequence of activities may not be a perfect sequence, i.e. there may still be dependencies above the diagonal. Those assumptions that remain are highlighted in the MDM. The feedback information flow between analysis activities C and A above the diagonal in Figure 3, results from dependencies between physical effects A → B and D → C. We highlight these couplings to signify that they represent parameters that need to be estimated and pose potential risks to the development process.

Alternative sequences of the activity DSM will lead to different assumptions in the physical effect DSM. Because some assumptions can be made with more accuracy than others, considering the highlighted couplings will support a robust planning of the campaign.

In this section of the paper, we have introduced a novel MDM, how to build it and how to analyze it. Let us now apply this method to a common system in nuclear fusion development.

4 Shutter system for optical diagnostics in nuclear fusion

There are many optical diagnostic systems in nuclear fusion reactors, most of which have a mirror close to the high-temperature plasma in the vacuum of the machine. It is of high importance for longevity to protect these first mirrors while the diagnostic system is in a non-measurement state. To this extent, designers have devised a range of shutter systems in a variety of technological concepts (Vorpahl et al., 2017). We focus on the shutter system of a particular diagnostic system, the Visible Spectroscopy Reference System (VSRS) (Ushakov et al., 2020): The shutter system consists of a pneumatic actuator that is located outside of the vacuum vessel; a feedthrough that transmits rotational motion to the in-vacuum side; a drivetrain of rods, bearings and gears; and a shutter blade that rotates 180 degrees around the vertical axis, blocking any molecules that may contaminate the first mirror.

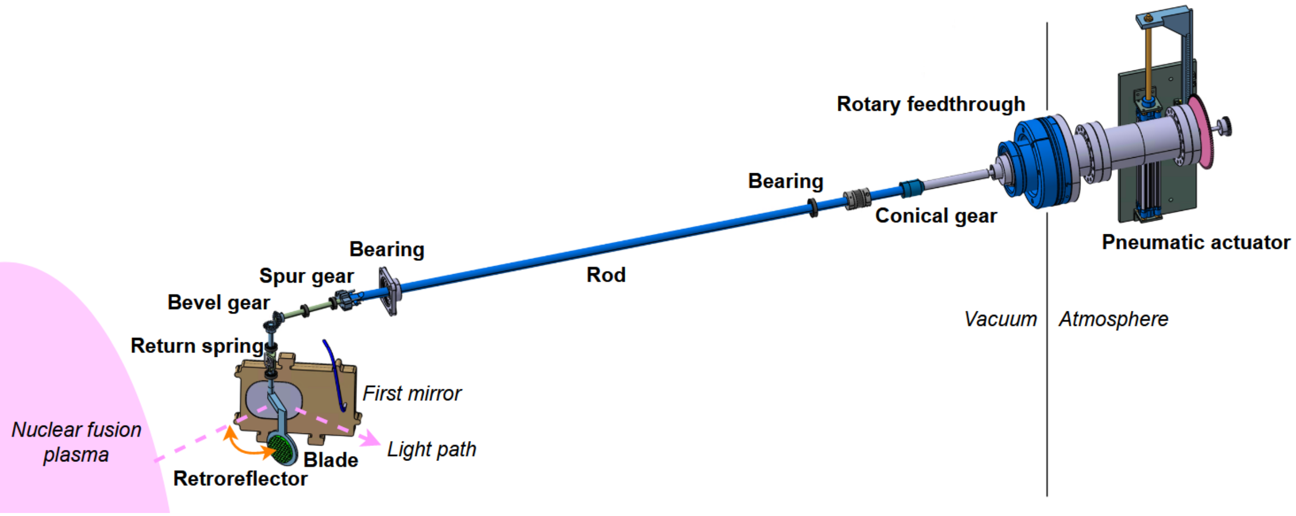

Figure 5. The elements of the VSRS shutter system, printed in bold font, operate close to the plasma of nuclear fusion reactors. A pneumatic actuator generates force that is transferred into the vacuum vessel through a feedthrough, gears, bearings and rods. The blade at the end of the drivetrain moves over the orange arrows such that it blocks the path between plasma and first mirror (pink). A supporting frame, end stops, a protective garage, piezo actuation valves, limit switches and a signal feedthrough are not shown.

Although Figure 5 might suggest that the design is relatively simple, analyzing the shutter is far from trivial. The physical conditions imposed by the environment of a nuclear fusion reactor include a magnetic field, vacuum, radiation, high temperature, ingress of exotic particles, mechanical vibrations and seismic activities, to name a few. These conditions have made the shutter system a perfect candidate for our method to plan a multidisciplinary analysis campaign.

The shutter system of the VSRS was at a preliminary design level when we conducted this exercise. Functional building blocks and interfaces were already defined, and technologies for the individual components had been selected. Except for some basic hand calculations for initial sizing and feasibility assessment, no analyses had been done yet. The data for the model was collected over a period of a few weeks. System architects provided most of the data, which was reviewed and validated by domain experts.

4.1 Multi-Domain Matrix

We have followed the steps in Section 3 to construct the MDM in Figure 6. Colored annotations provide additional details, which we will explain below.

Our analysis showed that the seventeen functional components of the shutter are subject to 52 physical effects. We use the colors green and orange to display that an effect is respectively desired (i.e. functional) or undesired (i.e. a disturbance). The central DSM contains the dependencies between these effects, which we have attributed a strength of one (weak), two (medium) or three (strong) and colored accordingly in green, yellow or red. We took into account two factors when defining these attributes: (1) The sensitivity of one effect with respect to another and (2) the uncertainty of this assessment, due to limited knowledge. Sensitive and uncertain couplings receive a higher strength than robust and certain ones. The effects are mapped to environmental conditions in the same manner, pictured above the physical effect DSM.

Figure 6 shows a component-based view. That is, all the physical effects of a single component form a cluster. This view intuitively represents physical couplings between components as inter-cluster dependencies. Alternatively, one can think of a discipline-based view, where clusters would represent physical effects of the same knowledge domain (e.g. mechanics and thermodynamics), and couplings are cross-domain effects and parameters (e.g. thermal expansion). Such alternative organizations of the physical effect DSM could lead to new insights, but are outside the scope of this work.

We expect that the project is most affected by physical tests, because they require the development of specific setups and prototypes. Therefore, we focused on modelling these activities, and disregarded numerical simulations. When defining these activities and mapping them to physical effects, we already experienced how the MDM could help to identify gaps.

Namely, we defined the first seven activities without the help of the physical effect DSM. However, when we projected these activities to the physical effect DSM, we found that there remained empty columns (highlighted in purple). These columns represent physical effects that would not be tested by any of the initially defined activities. Most of these effects were of lesser importance, indicating that the system architects were already focusing their activities. However, the projection matrix did highlight some important effects that were actually overlooked. We added a second set of activities to cover these overlooked effects. Two effects will still remain untested, but this was justified by the high maturity of the component and the low physical couplings to other effects.

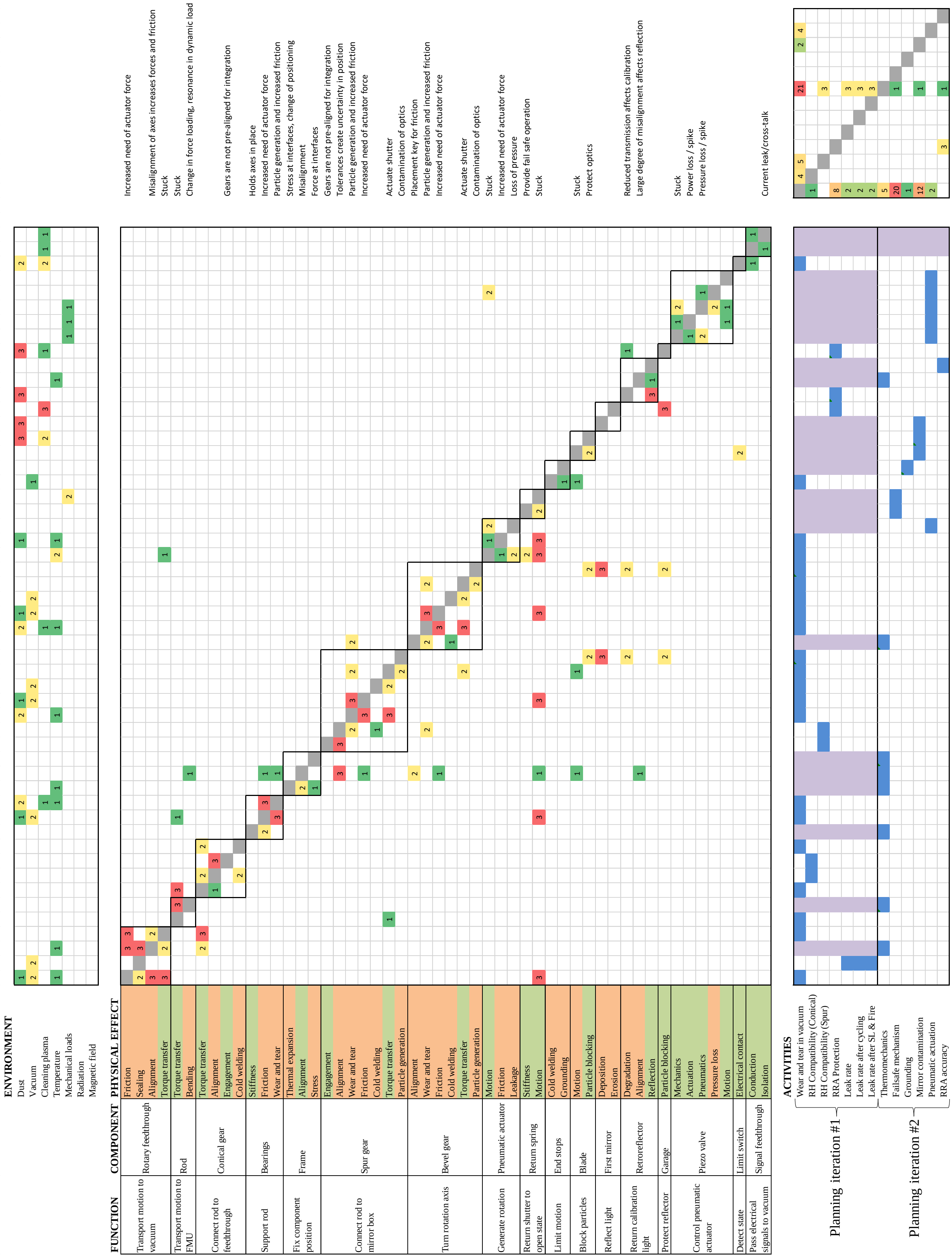

Figure 6. The Multi-Domain Matrix (MDM) represents the physical behavior of a nuclear fusion shutter system as a set of 52 coupled effects. Thirteen testing activities will analyze these effects in detail. Dependencies between these activities are displayed in the bottom-right matrix.

The MDM is completed by the square activity DSM, located in the bottom-right of Figure 6. We have identified the information flows in this matrix according to the steps in Section 3.3, where the dependency strength between physical effects served as a weight.

The effort of building the model in itself answers our first question: Are we complete? As described above, the mapping between effects and activities had been an indicator of the coverage of our planned analyses. But how can the model answer questions two and three: How to prioritize activities and what assumptions do we need to make?

4.2 Reducing assumptions through sequencing

The answer to the above questions lies in the activity DSM. We have rearranged rows and columns in a way that brings information flows underneath the diagonal. The result in Figure 7 is a sequence of activities in descending order of priority: 'Thermomechanics' should be analyzed first, 'RRA accuracy' last. The dependencies that remain above the diagonal signify assumptions to be made. For example, the 5 in the first row of the sequenced matrix means that analysts of the 'Thermomechanics' activity have to make an assumption on the outcome of the 'Wear and tear in vacuum'. If in a later stage the feedback from the latter activtiy is not in line with the assumptions, the former needs to be repeated. The 'Wear and tear in vacuum' activity seems to be a critical gate in the analysis campaign.

Wear and tear in vacuum		4	5					21			2	4	
RH Compatibility (Conical)	1												
RH Compatibility (Spur)								3					
RRA Protection	8												
Leak rate	2							3					
Leak rate after cycling	2							3					
Leak rate after SL & Fire	2							3					
Thermomechanics	5												
Failsafe mechanism	20							1					
Grounding	1												
Mirror contamination	12							1					
Pneumatic actuation	2												
RRA accuracy				3				1					

Thermomechanics					5								
RH Compatibility (Spur)	3												
RH Compatibility (Conical)					1								
Pneumatic actuation					2								
Wear and tear in vacuum	21	5	4	4		2							
Mirror contamination	1				12								
Failsafe mechanism	1				20								
RRA Protection					8								
Leak rate	3				2								
Leak rate after cycling	3				2								
Leak rate after SL & Fire	3				2								
Grounding					1								
RRA accuracy	1							3					

Figure 7. Initial (left) and sequenced (right) activity DSM. Numbers in this matrix represent the amount of analysis results that need to be transferred between activities. By rearranging rows and columns, strong dependencies are moved underneath the diagonal so that the chances at rework are minimized.

How can we further assess the assumptions above the diagonal for their practicality or feasibility? We have programmed the steps in Section 3.4 to highlight assumptions in the physical effect DSM. In Figure 8, we compare the DSM for the initial and the sequenced case. Those dependencies that will be covered by the analysis campaign are shaded grey, such that those dependencies on which we have to make assumptions are highlighted. We can now ask whether we can realistically make assumptions at these instances, or whether we would rather trade off a single difficult assumption for multiple easier ones.

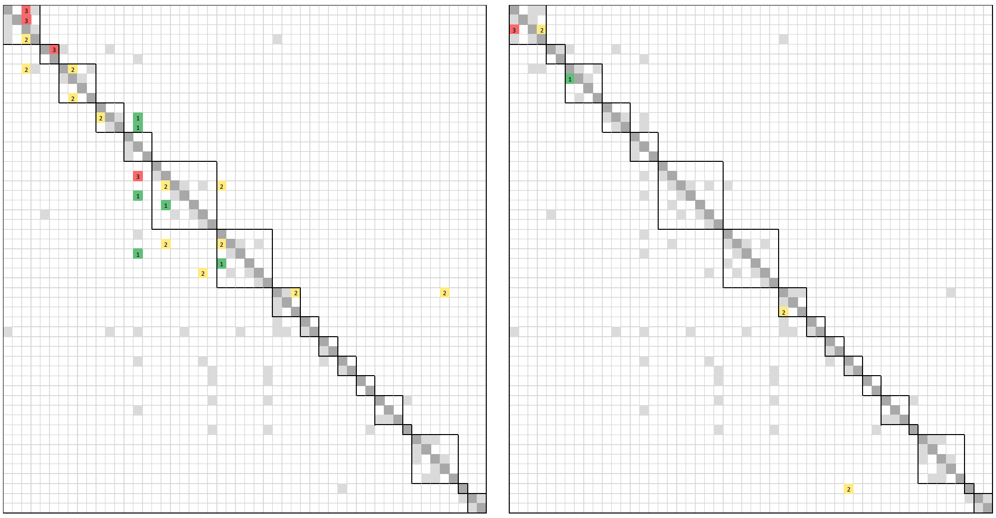

Figure 8. The physical effect DSM highlights the physical couplings that require assumptions for a given analysis plan. Sequencing the activities reduces the sum of these assumptions from 42 (left) to 10 (right).

The act of sequencing changes and significantly reduces the sum of remaining dependencies in the physical effect DSM from 42 to 10. These numbers are equal to the sum of feedback marks in the activity DSMs in Figure 7.

4.2 Lessons learned

We summarize some key takeaways from this exercise:

- Setting up the physical effects DSM is a powerful way for identifying new effects and couplings. The method inquires modelers to explore not only the breadth of effects that can occur, but also the potential coupling of every pair of effects (e.g. does temperature have an impact on friction?). This promotes the kind of systems thinking that is complementary to the distributed nature of the subsequent analysis activities.
- The DSM seemed limited in its ability to cover all aspects of physical behavior. In particular, it is impossible to define discrete events (e.g. a gear getting stuck or a piston losing pressure) and conditions for effects to occur (e.g. a gear engages during assembly but transfers torque during operation). Other process models, such as state charts, could be complementary in a larger framework (Browning, 2009).
- Cycles in the physical effects DSM can show escalating behavior. For example, we have found on multiple occasions that 'Friction' and 'Wear and tear' are mutually reinforcing effects. If designers look at these effects individually, they are missing important emergent behavior.
- We have even found that the DSM can provide valuable design feedback, in spite of its high abstraction level. The DSM makes it easy to identify sensitive components, i.e. those with many physical internal and external dependencies. If possible, these components should be avoided. While generating the model, we realized that some couplings had already been diminished or removed by earlier design decisions. We have recorded the following instances:
    - Instead of selecting a flat mirror to reflect light, designers had opted for a retroreflector. The latter is robust against angular displacements.
    - A pneumatic actuator is insensitive to the magnetic field in the reactor. For this reason, an electromechanical actuation concept was discarded in an earlier stage.
    - The shutter system in itself minimizes the flow of particles that would contaminate sensitive optics.

  The physical effect DSM would have visualized undesired couplings in all of the above cases.
- Defining a set of analysis activities is ultimately a resource allocation problem, constrained by the availability of money, knowledge, and tools. Although we did not consider those constraints in the current paper, we are confident that the MDM can be expanded with more matrices to represent these constraints.

5 Conclusions

Future nuclear fusion reactors will be subject to a wide range of physical conditions. Different aspects of the physical behavior are often analyzed in distributed activities, such as prototype tests or numerical simulations. In order to plan and coordinate these activities effectively, system architects, project managers and domain experts need an integrated view on both the engineered system and project resources. In this paper, we have presented a systematic method for the planning of such activities.

Our method revolves around a Multi-Domain Matrix (MDM) model. One view of this model is a matrix of coupled physical effects, representing the behavior of the engineered system. This view complements the system's functional architecture, which is defined in terms of functions and components. The second view contains a matrix of the planned activities that will analyze individual effects in detail. The projection matrix between these views directly indicates how well the activities cover everything there can be analyzed. The model can prioritize activities through the act of sequencing, and highlight which physical parameters need to be estimated in order to start the analysis campaign.

The model is sufficiently abstract and domain-independent for project managers, system architects and domain experts alike. This makes it a useful tool in early planning stages of engineering projects. We have even found it a cost-effective way to identify undesired behavior and improve the design for robustness, without the need for detailed analysis. In later execution stages, the model supports coordination and change management.

We have applied the method to a common subsystem in nuclear fusion reactors: an optical shutter. We could formalize and visualize the behavior of the system as a set of 52 interdependent physical effects. Linking these effects to thirteen test activities has significantly supported the planning of the project. We expect that the MDM can easily be expanded to concurrently manage information from other domains, such as responsible actors, knowledge disciplines or analysis tools.

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