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Material flow planning in fusion test facilities

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ABSTRACT

Fusion test facilities are expansive, intricate structures designed to test materials for fusion power plants. For a seamless testing process, it's crucial that the machinery and equipment within these facilities are consistently maintained and promptly replaced if they fail. This necessitates the transportation of large, heavy machinery and equipment through the facility's narrow corridors, doors, hatches, and shipping bays. Taking the DEMO oriented neutron source (DONES) as a case study, we illustrate the complexities of material flow planning in such environments, detailing strategies to navigate these challenges and organize material flow planning efficiently and safely. We introduce a methodology for executing various stages of material flow planning in these contexts and discuss how uncertainties impact the planning process. The primary hurdles include gathering data on machinery and equipment and the facility's layout, converting this data into actionable transport plans and routes, providing precise transport instructions, and verifying the viability of the material flow. We propose and implement a comprehensive solution to these challenges at DONES, encompassing data collection techniques, the creation of a modular transport system, a universal model for transport processes in intralogistics, and a simulation tool for swift and effective collision checks between transport devices, machinery, equipment, and the building structure. A significant insight from this approach is the high value of automating the process, as uncertainties frequently alter data, necessitating regular updates to the material flow plan.

1. Introduction

The physical challenges of developing fusion energy and commercializing energy from fusion power plants are often the focus of public attention. However, the engineering challenges, while demanding, remain at the forefront of current research efforts [1,2],. Within these engineering tasks, ex-vessel operations such as 'delivering tools, removing radioactive components into storage, and then introducing clean or refurbished components is also a significant challenge' [2].

These challenges become apparent when looking at the planned large research and energy production facilities in Europe, such as the International Thermonuclear Experimental Reactor (ITER), the Demonstration Power Plant (DEMO) or the European Spallation Source (ESS). These facilities consist of large buildings with many different components and systems interacting with each other, posing engineering challenges. During the design phase, a common characteristic of these projects is the continuous evolution of systems and components. Therefore, the design of one system depends on the changing characteristics of other systems. In addition, these projects involve integrating systems such as building design or logistics and maintenance. In the latter, components, building layouts, and maintenance processes must be coordinated, and a material flow must be defined for transporting components during maintenance. Another research facility where logistics and maintenance planning are a challenge is the DEMO Oriented Neutron Source (DONES) project. The DONES project is a planned material testing facility for the qualification of materials to be used in DEMO. Materials will be continuously irradiated with neutrons to test the effects on the materials. The testing is organized in 2-year phases, and after each phase, components must be removed, and clean components introduced [3]. For both, the material flow must be planned for these transport tasks as well as for unforeseen maintenance tasks. A valid material flow ensures that all necessary transports are performed with a quality that respects the sensitive components of a nuclear fusion facility.

We describe material flow planning in fusion facilities using the example of material flow planning in the DONES project.

First, Chapter 2 discusses the material flow planning process in literature and in nuclear fusion facilities. Afterwards, Chapter 3 presents

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the challenges of the material flow planning in the fusion environment and Chapter 4 provides an overview of the material flow planning process developed for DONES. Chapter 5 explains the used methods and established processes in detail. Finally, Chapter 6 sums the whole process up and gives an outlook to future research.

2. Literature review: material flow planning – industry standard and fusion

Material flow planning is well established in the literature, especially for industrial material flows. Usually, industrial material flow planning has a different objective compared to material flow planning for nuclear fusion facilities. As pointed out by [4], the starting point for material flow planning in industry should be knowledge of the aimed operational throughput of the system and a redundancy-free database. [5] identifies 4 main constraints to be considered for material flow planning in an industrial environment. The time of material flow (throughput), the quality of transportation, economic considerations, and the flexibility of the material flow system.

It is evident that the objectives of material flow planning for fusion facilities are slightly different. The time of movements and the throughput of the system are not key objectives, nor are the economic constraints. The other two constraints are more important and determine the direction of research: The quality of transportation and the flexibility of transportation. These include safe transportation without clashes between components and buildings, and the need for only a few transportation devices for many different components and tasks.

Some parts of the process presented in Chapter 5 are already available in the literature. The choice of the right transportation device is described with an optioneering approach and the involvement of experts [6]. Furthermore, the details of the transportation device planned for DONES are presented in [7] and [8]. [9] shows how different scenarios in DEMO are evaluated in terms of time and potential clashes between components and the building.

[10] and [11] are similar to the work presented in this paper. However, in [10] the clashes are analysed only near the end point of the transports and in [11] only one component is shown. Especially the variety of components in DONES requires a new approach. In [12] an approach for the planning of maintenance tasks is presented, which also includes a material flow planning. This approach is dedicated to DEMO and contains similar methods that are also presented in this paper.

Finally, [13] presents an approach how the use of a digital twin could further improve the planning process presented in this paper and could also lead to a connection between the current planning process and the logistics in operation during the operational phase of fusion facilities.

In summary, this paper presents the material flow planning process in DONES. In fact, some of the methods presented in this paper can already be found in existing literature. The method of step 2 is already presented in [7] and a clash analysis in step 4 is also performed in [10] and [11] (for the steps see Chapter 4). In [12] the same simulation software is used for the clash analysis as in this paper. However, steps 1, 3 and 5 are new and have not yet been published in the literature. Although [12] also presents a comprehensive material flow planning, the main difference is the focus of the work. This work assumes that finding one feasible solution is already a success, while [12] assumes that multiple feasible solutions may exist.

3. Challenges in material flow planning in nuclear fusion facilities

All challenges faced by material flow planners in nuclear fusion facilities are because research facilities are highly volatile in the design phase. The layout of the facility affects the dimensions (weight and size) of the components to be transported and vice versa. As both change over time, the material flow must also adapt. Furthermore, the components have large dimensions (up to 140t weight and 140m^3 space reservation) and the buildings of these research facilities have limited space. In addition, due to the nuclear environment, some transportation must be done remotely, and the operators must comply with safety standards.

The challenges the material flow planners faced in DONES are in detail:

- **Database**: The DONES project utilizes the ITER Document Management (IDM) system as its database for research, inheriting both the benefits and drawbacks of such an archive. A notable drawback is the lack of redundancy-free information. This issue affects both components (dimensions, weight, transportation frequency, origin, and destination of transport, etc.) and buildings (door sizes, airlock functionality, wall placement, etc.). The challenge with databases lies in overcoming these drawbacks to create a redundancy-free data structure for components, layouts, and transportation tasks, all while adhering to the DONES project's requirement to use the IDM system as the sole data supplier.
- **Changing Environment**: Research facilities undergo changes during the design phase. In DONES, the most significant alterations are driven by ongoing research in core systems (Test System, Acceleration System, Lithium System), affecting data, tasks, and associated transportation devices. This dynamic environment may necessitate new components, requiring entirely new transportation devices and routes. Moreover, material flow requirements, particularly concerning nuclear safety, are subject to change.
- **Interface System**: Logistics is an auxiliary system, meaning any changes needed in terms of material flow must be coordinated with all related systems. A process that can be both time-consuming and prone to errors.

4. Material flow planning process overview for dones

As mentioned in Chapter 2, the material flow planning for fusion facilities differs from the standard approach for material flow planning. The task for material flow in DONES is defined as the transportation from the warehouse of DONES to the rooms of installation of the components and placement of the components on the ground as well as the transportation from the ground of the rooms of installation to rooms for treatment of irradiated components back to the warehouse again.

The process steps shown in Fig. 1 are:

- **Step 1**: *Create a redundancy-free database* [4]

This step is standardized and performed once a year at the beginning of material flow planning. Chapter 5.1 discusses this in detail and presents the database approaches.

- **Step 2**: *Select transportation device*

This refers to the selection of the transportation devices based on the available information about the components and the building layout (see Chapter 5.2). The selection of transportation devices is manual but based on defined requirements.

- **Step 3**: *Find a transportation path for every transportation task* (see Chapter 5.3)

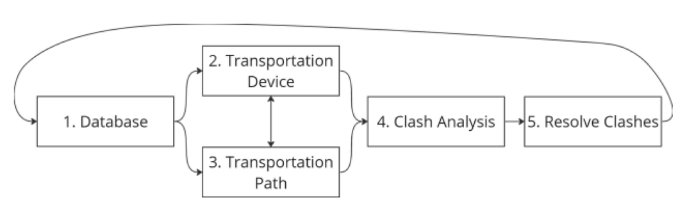

Fig. 1. Overview of the Material Flow Planning Process.

Due to the additional context needed which is based on the experience of the planners within the DONES project, this is a manual step. Note that step 2 and step 3 are interrelated, and feedback loops between these steps may be required.

- **Step 4**: *Perform a clash analysis*

The combination of components, transportation devices, transportation paths and buildings can lead to clashes which must be avoided. In industrial environments this is usually not a critical point, but the corridors in fusion facilities are rather narrow compared with the dimensions of components. This clash analysis is performed with use of an AnyLogic simulation (See Chapter 5.4).

- **Step 5**: *Resolve clashes*

If conflicts are identified in step 4, they must be resolved before the next iteration can begin. For this purpose, a standardized process with all affected systems is established and presented in Chapter 5.5.

The process must be repeated whenever there is a change in either a transportation device, component or the building layout. The standardized and automated methods have the main purpose to save time for the planners and avoid human errors.

5. Material flow planning methods

Following the planning process presented in Fig. 1, we introduce five material flow planning methods. Each method is dedicated to one step of the material flow planning process. A redundancy-free database for the components to be transported and the transportation tasks is introduced in Chapter 5.1, the choice of transportation devices is presented in Chapter 5.2, the path planning is explained in Chapter 5.3, the clash analysis in Chapter 5.4, and the change process in DONES is shown in Chapter 5.5.

5.1. Databases

In research projects, data management is usually not the most prioritized part of the project. This leads to archive-like databases, which is the reason for accessing several different data points. For example, there are sources for both 20t and 30t weight of a single component. The same is possible for the length, height, weight, transportation frequency, transportation orientation, and sensibility of components, as well as the transportation tasks themselves. This can lead to the planning of a transportation task with obsolete information, resulting in transportation paths ending up in the wrong place or transporting the wrong components.

Hence, a special database is established within the IDM where all relevant data is collected, serving as the single source of truth for material flow planning [14]. The database is updated once a year and distributed to all affected coordinators in DONES for feedback and review. After that, this database is the only source of data and information for the material flow planning for the following year. In this way, a redundancy-free and consistent database is established.

The database is divided into two parts. First, information about components is collected, and second, information about transportation tasks of each component is included in the database. The most important component information include: ID, Plant breakdown structure, name, CAD figures if available, storage rooms (starting point of transportation), rooms of installation, rooms after operation, length [mm], width [mm], height [mm], weight before operation [kg], weight after operation [kg], remote handling or hands on, level of contamination and activation after operation, frequency of replacement and rotatability of the component.

The second part of the database includes:

- The exact start location for every transportation (x, y and z coordinates in the DONES global coordinate system)
- The exact end location for every transportation (x, y and z coordinates in the DONES global coordinate system)

This part of the database contains not only the center coordinates of the components, but also the coordinates for each corner of the component, as well as the coordinates for each corner of the transportation device and the transportation aid (both will be introduced in Chapter 5.2 as well as in [7]). The exact definition of the start and end locations allows the material flow planners not only to get direct feedback on the feasibility of the transport, but also nudges the coordinators to give feedback if the affected area is used and planned for other tasks in the near future. The database described in this chapter guarantees a consistent basis for planning and creates efficient interfaces between logistics and other systems of DONES, while adhering to the DONES project's requirement to use the IDM system.

5.2. Transportation device choice

As shown in [1] and mentioned in Chapter 1, performance and cost are interdependent. Especially in the fusion context, quality is important because components are usually very expensive, with long lead times and long production times for prototypes. This means that the quality of the transport is equal to the safety of the transport. However, it is desirable to achieve this safe transportation at minimal cost. Under this premise, the requirements for a transportation system are [7]:

- Transportation of all components through narrow corridors and doors.
- Transportation of heavy components.
- Emission-free operation.
- Operation without additional infrastructure.
- Wireless and remote control.
- Movement within rooms, shipping bays or airlocks.
- Rescue and recovery scenarios.
- Radiation hardness of the transportation system, which includes a high lifetime of the system as well as low maintenance intensity.
- Movement outside between main building and warehouse.

The result of the analysis is a modular transport system [7]. It consists of a standardized pallet as a transport aid and a standardized ground based omnidirectional electric powered mover as a transport device. Components can be placed on one or more pallets, and the movers can drive under the pallets and lift the pallets in synchrony. The transportation is also synchronized. The component mounted on pallets and transported with the mover is defined as a Total Transportation Unit (TTU).

When the transported components are activated, two options for handling these components are analyzed. The first possibility is to shield the environment from radiation by using casks, which increases the dimensions of the TTU. The dimensions of the TTU including the casks lead to many collisions between the TTU and the building and is not the currently preferred option. The second option is that the transportation system ensures fast transportation through the corridors that are temporarily closed to workers and the ability of the transportation system to recover in the event of a disaster. The second option is currently being evaluated with industry partners.

In [7] a detailed analysis is presented that justifies the choice of the transportation device. It also explains why off-the-shelf solutions are not applicable to DONES and may not be an option for other research facilities. In addition, [7] presents a cost model to compare the "one transportation device fits all" approach with the approach of selecting an individual transportation device for each component.

In the dimensioning of the pallet and the mover, two opposing effects are considered:

1. Larger pallets and movers can carry heavier components.
2. Smaller pallets and movers can drive into more rooms.

The evolving development of electric omnidirectional movers lead to small movers and pallets with which it is possible to access all rooms of DONES. Therefore, the modular transportation concept does not have to be changed for every iteration of the material flow planning process.

5.3. Path planning

The path planning is based on the database from Chapter 5.1, the transportation system and the building layout. Methodologically, this is the only manual step. The main obstacle in automating this process step is that feasible paths that don't cause clashes between the TTU and the building don't exist for all components, which is an example requirement in [12]. So far, there are always clashes in the first iteration of the process described in Chapter 4, which is performed only when a component, layout, or transportation system changes.

First, the building layout is analysed, and many different paths are proposed for the components. In DONES, most of the paths cause clashes and therefore an individual evaluation of the proposed paths and the chances of solving the clashes that occur must be evaluated. Such clashes are for example doors that are too small, pipes and ducts that hang too low, airlocks that are too short, and corners that are too narrow. During path planning for DONES, the following clashes occurred and had to be resolved (for details on how to make changes, see Chapter 5.5):

Doors

- Increase doors in width and height.
- Change opening direction of doors.
- Wing-based or roll-up door.
- Placement of doors.

In a nuclear environment, doors have a contamination containment function, which complicates the replacement of doors. This reduces the maximum size of doors, and these doors must be custom made, which is one reason why building designers want to strive for standardized doors. In addition, changes in doors lead to other changes in the building, such as pipes and cables running above the doors.

Shipping Bays

- Size of lifting platform and therefore the shipping bay itself.

Shipping Bays are hoistways. They connect all floors of a building. This means that changes in the placement and dimensions of such a hoistway will result in further changes on all floors of a building. Therefore, such changes should be avoided if possible.

Hatches

- Dimensions of hatches.

Hatches connect floors by essentially making a hole in the floor of the upper floor. Modifications are relatively easy, as hatches usually connect two rooms with similar radiation levels.

Air Locks

- Dimensions of air locks.

Airlocks connect two rooms with different radiation levels. Typically, airlocks are designed too small to accommodate all the necessary components. Enlarging airlocks is controversial because additional space in airlocks results in less space in adjacent critical spaces. If possible, such changes should be avoided.

Ducting, Piping and Cabling

- Placement of ducting, piping, and cabling.

These are minor clashes and relatively easy to resolve. For example, if cables are planned in front of a door and the door height is increased, the cables must be replanned. Ductwork is more difficult but can usually be worked out with the building designers.

Walls and Shape of Rooms

- Replacement of walls.
- Change in shape of rooms.

These changes are one of the most complex changes in the building layout. Many different aspects must be considered: the structural integrity of the building, ducts, cables and pipes, doors in these walls and rooms, columns with the purpose of structural integrity of the building. In the latter case, the seismic integrity of the building must also be considered.

Research Site

- Suitability of surface material of outside roads and paths.
- Size and properties of point of operation for crawler cranes.

Changes outside the buildings can be quite easy or quite difficult. For example, the proposed movers will need a smooth surface of the path as well as a hard surface (e.g. concrete instead of asphalt). Since the roads and paths of the DONES property are not yet built, such changes can be easily implemented. On the other hand, the need for crawler cranes for the initial installation and replacement of very heavy components will require a large and resistant area for cranes outside the building. This should be planned as early as possible, as it may lead to the relocation of other buildings already planned.

Weight of Components

- Matching between weight of components and payload of the transportation system.

This appears especially when using cranes. This is a hard to resolve problem since either cranes with higher payload need to be used, which are usually too large for the available space, or the component must be changed. This should be avoided.

5.4. Clash analysis: anylogic simulation model

After considering all the previously mentioned possible clashes and difficulties in resolving them, a small number of possible material flows remain. With the commercial simulation software AnyLogic we can implement two automated tasks: Check for clashes and measure transportation time.

Fig. 2 shows the user interface of the AnyLogic simulation. The working principle is the following:

1. Read and convert input documents.
2. Implement possible paths.
3. Mathematically check for clashes (See [15] for details).
4. Time measurement during check for clashes.

The simulation is based on the 2D layout of the main building. The walls are replicated in AnyLogic, which converts the 2D drawings into a 3D environment. The TTU is modelled as an agent that moves through the 3D building. As shown in Fig. 2, the paths for the TTU are in the geometric centre of the corridors. Traffic in the building is expected to be low, and for this reason we do not expect two TTUs to travel in opposite directions in the same corridor at the same time.

The input document consists of a list of components with all necessary information (dimensions and weight) and description of their possible paths through the building. The simulation calculates a TTU from the component dimensions. First the number of pallets is calculated and then the bounding box of the TTU is calculated. This bounding box is

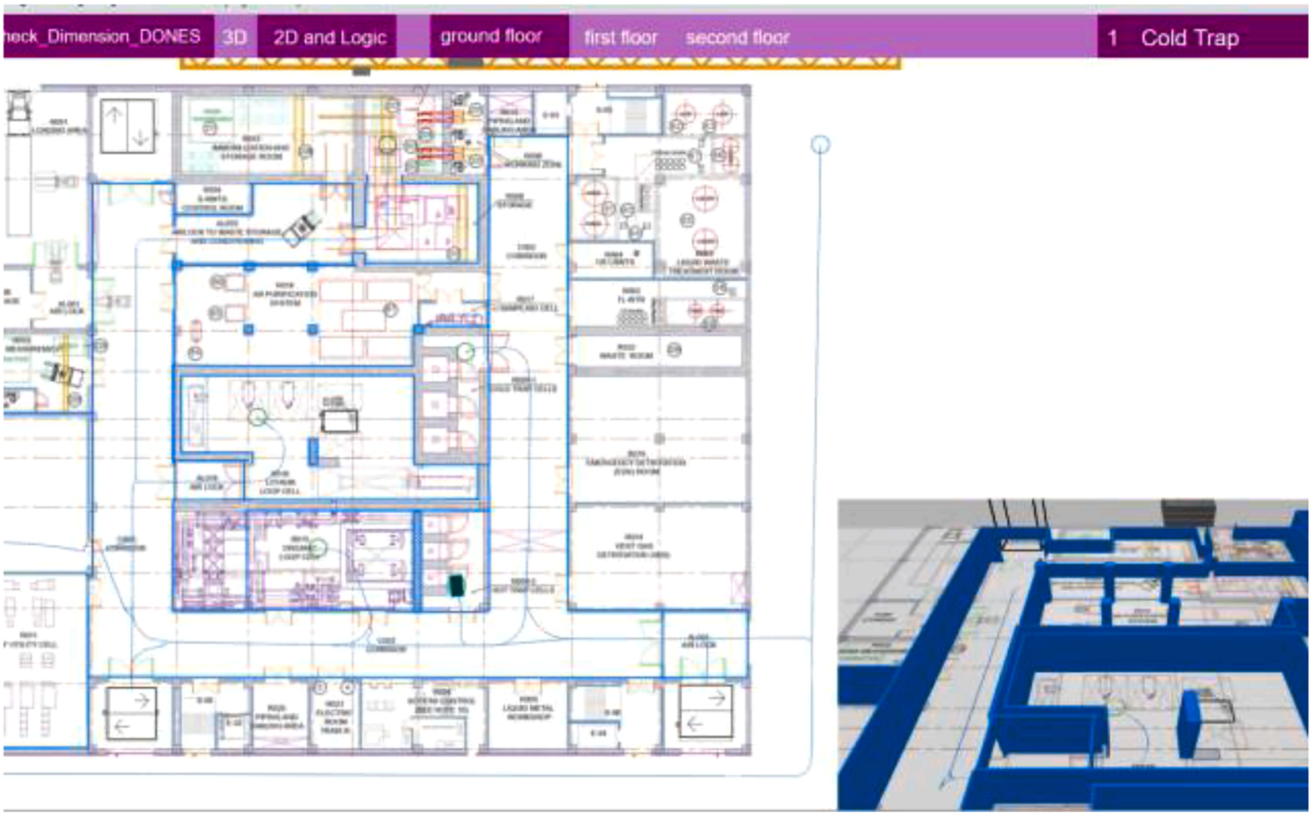

Fig. 2. Screenshot of the AnyLogic material flow simulation.

then moved through the building and a clash analysis is performed at each possible clash site (e.g. the height of the TTU plus a safety margin is compared to the height of a door). The results of all the checks and the transportation time are the output of the simulation and can be used to decide which paths result in the least number of changes and the least change effort for the project.

5.5. Change process in dones

The final step in the material flow planning process is to implement changes to the building layout or components. Some components can be adapted for transportation (e.g., assemble bulky parts in the final room of installation), but in general the building must be changed. It is important to have a standardized change process for several reasons:

- A standardized process ensures, that all affected systems of the research facility are involved, and important aspects are not missed.
- The time between initializing and implementing of a change request can be reduced.

The material flow planner can use standard project change processes which can be supported by the results of the described automated processes.

6. Conclusion

This paper shows how the use of tools, and the automation of processes can improve material flow planning in fusion research facilities. We have presented a structured material flow planning process consisting of five steps that can and should be applied to other research facilities. In particular, the introduction of a redundancy-free and consistent database in combination with the AnyLogic clash detection simulation improved the quality and performance of the material flow planning significantly.

Although the material flow planning has been improved in the last few years, there is still room for improvement. Currently, we only know that the transportation of components considered in isolation works. However, we cannot assess whether the overall maintenance logistics processes are working and whether the maintenance time targets can be met.

We propose to implement additional tools in the future and to collect additional information in the database:

- Maintenance resource allocation planning and optimization. We currently only assess the material flow from a qualitative point of view. But the throughput should also be considered (for resource allocation approaches in fusion facilities see [16]).
- The path planning is the only manual and non-standardized step in the material flow planning process. This should be automated as well in the future.
- Add information concerning the volume of the TTU before and after operation in case the dimensions of a component change during operation.

CRediT authorship contribution statement

Timo Lehmann: Conceptualization, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Georg Fischer:** Conceptualization, Methodology, Writing – review & editing. **Felix Rauscher:** Conceptualization, Methodology, Writing – review & editing. **Sebastian Köhler:** Conceptualization, Methodology, Writing – review & editing. **Fernando Arranz:** Conceptualization, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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