

Quantitative Space Requirement Analysis for Construction Logistics Planning

Master thesis: Construction Management & Engineering

Author: J.M.A. Lodewijks, BSc
Master student Construction Management & Engineering
3TU Federation – University of Twente

Supervisors: University of Twente Ed. Züblin AG

Dr. T. Hartmann Dipl.-Ing. K. Kessoudis
Dr. S.H. Al-Jibouri

Abstract

The introduction of 4D-CAD models in the construction industry has enabled planners to conduct a variety of optimisation processes prior to construction. One of those optimisation processes that can decrease project cost and duration is the planning of onsite construction logistics of materials. The need for visualising and planning construction logistics stems from the increasing demand to construct faster and cheaper. This thesis presents a method for quantifying the space requirements of materials needed in construction logistics planning.

The proposed Quantitative Space Requirement Analysis Method, in short QSRA-Method, was developed based on existing literature and tested on two illustrative example projects, a high-rise building and an airport terminal.

To validate the QSRA-Method, the method and in particular the output was discussed with a select group of construction planners and construction IT specialists. The output of the method was appraised as useful for supporting material procurement and storage decisions and capable of providing more information than existing methods.

Keywords: Construction logistics; Material storage; Material space requirement;

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1 Introduction

In 2008 the 5D Initiative (www.5d-initiative.eu) was founded by five European construction companies: Ballast Nedam, Royal BAM Group, Consolidated Contractors Group S.A.L. – Offshore (CCC), Max Bögl and Züblin/Strabag. The 5D Initiative is an independent task force and think tank within the European Network of Construction Companies for Research and Development ENCORD (www.encord.org). The goal of the initiative is to describe common requirements of the European construction industry for the development of new innovative tools by the hard and software industry.

Züblin – one of the 5Di-partners – is momentarily focussing on developing tools for visualising and planning on-site construction logistics within the German research project Mefisto (www.mefisto-bau.de).

The need for visualising and planning construction logistics stems from increasing demands to construct faster and cheaper. In order to meet such demands, general contractors often increase the amount of work done and hence resources used per time unit, and schedule activities concurrently. These strategies increase the use of space, which subsequently results in an increase in time-space conflicts (Akinici et al., 2000a).

To increase the efficient use of site space and manage the increase in time-space conflicts, Züblin wants to visualise the construction logistics process. In particular the flow of materials on site, since deficiencies in the supply and flow of construction material are often adduced as major causes of productivity degradation and financial losses (Thomas et al. 2005).

This thesis thus presents a method for quantifying space requirements of materials to enable construction logistics planning. Construction logistics planning in this thesis will be defined as ‘the combined planning of material procurement and material storage’ (Said & El-Rayes, 2010). The proposed method: the ‘quantitative space requirement analysis’-method or QSRA-Method, will

enable planners to analyse and quantify material space requirements so that they can be used as input for construction logistics planning.

The goal of this thesis will be:

- To create a method that enables the quantification of material space requirements,
- To create a time efficient alternative to existing methods,
- To represent the material space requirements in such a way that they support both material procurement as well as material storage planning,
- To represent the material space requirements in such a way that they can be entered back into a 4D model,
- To quantify and represent material space requirements,
 - per task
 - per construction section
 - per time unit
 - on a numerical value basis (e.g. m^2 , m^3)
 - on a geometrical parameter basis (e.g. width, length, height).

2 Research Method

2.1 *The literature review*

The first step in the research method was to conduct a literature review of research in the fields of space planning, site layout, material procurement, n D-modelling and warehouse space planning.

The focus of the literature review within space planning research was on finding the decision processes in space planning and the factors that influence those decisions. This helped to understand the consequences of the problem (an increased demand for site space) and the need for construction logistics planning.

The literature review of site layout research focussed on finding the way in which modelling efforts helped planners make construction logistic planning decisions. This helped understand how previous research modelled available and required space. The literature study focused on quantitative methods because the research literature of space planning had shown that the decisions made in construction logistics planning required a quantitative approach.

Since quantifying material space requirements requires knowing the quantities of materials on site, material procurement research was studied. This research helped understand the procurement decisions which also have to be supported by the QSRA-Method. Furthermore it showed that material storage and material procurement planning are very interdependent, hence both issues are addressed in this thesis.

The aforementioned space planning and site layout research made extensive use of 3D and 4D models. Thus a review was conducted of research wherein n D-models were applied to construction projects. This was done to assess the need/usability of applying n D-models in this research endeavour.

On the basis of a literature review, no method for quantifying material space requirements in the construction industry was found. For this reason, literature in warehouse space planning was studied. The methods used for quantifying space requirements in this field were analysed. This

helped to serve as a foundation for building the QSRA method which is adapted to the construction industry context. This concluded the first step, the literature review.

2.2 Developing and validating the method

The next step was to create the QSRA-Method, which was done in close integration with existing literature. The QSRA-Method was developed incrementally during an iterative process wherein the method was applied and tested on two example projects (see next section). The method was validated by applying it under the supervision of construction planners and discussing the usability of the results. The validation method is described in more detail in section 6.1. This is done because a proper understanding of how the validation was conducted requires some understanding of the QSRA-Method itself, which will be presented in chapter 4.

2.3 The illustrative example projects

For demonstration of the use of the developed method two contrastive projects were chosen: An airport terminal (fig. 1) and a high-rise building (fig. 2).

The airport terminal project has a large amount of materials of a multifarious nature. This is considered ideal for testing whether the QSRA-Method can create recipes that will quantify material space requirements.

In contrast to the airport terminal project, the high-rise building project has a small but high construction site. Hence the applicability of the QSRA-Method was tested in very different settings. This will add to the generalizability of the results of this thesis.

Both example projects already had a 3D-CAD model that could be linked to a digital schedule and to a digital cost model which was based on a Work Breakdown Structure (WBS). This is an important amenity of the example projects. It means that the available information represented the amount of data, the level of detail of the data and the representation form of the data as it was available; not as was needed for the QSRA-Method. Thus the example projects reflected a real situation, wherein the

data already exists in a digital format and needs to be restructured (subprocess 2, I.I; see fig. 8) so as to make it applicable for the QSRA-Method.



Figure 1: Example project airport terminal



Figure 2: Example project high-rise building

3 Theoretical points of departure

This chapter describes some related previous research to provide theoretical points of departure for developing the proposed method; in this study referred to as the QSRA-Method. During the explanation of the QSRA-Method in chapter 4, there will be frequent reference to this chapter to clarify the link between the theory and the way the method is developed.

Chapter 3 is structured as follows: The next section will explain what decision processes will need to be supported by the quantified material space requirements. Furthermore the section will show *what* and *how* preconditions must be met. Section 3.2 will show how material space requirements will need to be represented and elaborate on the way they need to be modelled in 4D-CAD. As than the prerequisite conditions for quantifying material space requirements are described, a material space quantification method from warehouse management research will be presented (section 3.3). This method was used as starting point for creating the QSRA-Method presented in chapter 4.

3.1 Construction Logistics planning

Existing research has mainly investigated material procurement and material storage independently. This research will consider both issues, since they are mutually interdependent. To clarify: material procurement decisions are greatly dependent on (1) the criticality of the construction activities consuming the material and (2) the site space available. Likewise, the number of possible site layouts is dependent on (1) procurement decisions made, (2) storage space needs and (3) the location of temporary facilities. (Said & El-Rayes, 2010).

3.1.1 Material procurement decisions

Ideally in procuring materials for construction, decisions need to be made to ensure that there is an optimal quantity of materials on site at all times. Planners face several dilemmas in making the decisions on how much material to order. Due to uncertainty in construction projects, inventory buffers are needed. Too large material buffers in the inventory are wasteful and impede workflow, whereas too small buffers increase the probability of material shortages and subsequently project

delays (Thomas & Horman, 2005). Procuring larger amounts might result in lower unit costs, however the planner has to be able to decide whether there is enough site space available to procure such large amounts.

Practical implication for the method:

To support the above described decision making on material procurement, a **quantification** of material space requirements is necessary. Planners need to know how much site space is available to create inventory buffers and they need **to know how quantities of materials will translate into use of site space.**

3.1.2 Material storage decisions

Material storage planning needs to ensure that the quantities of materials (as procured) are stored on site, to enable the smooth execution of the on-site construction process. To define where materials should be stored on site, planners try to minimise *transportation costs* – the costs associated with transporting the materials from the storage location to their respective location of use – and *relocation costs* – the costs associated with relocating materials from one storage location to another (Zouein & Tommelein, 1999). In effect this will result in minimal material handling.

Apart from where materials can be stored, planners also need to consider that materials can have different space requirements depending on their nature and the activity they are being used for. Formwork for example requires more space when it is being cleaned than when it is being stored or built in.

Practical implication for the method:

To support the above described decision making about material storage, again, **quantification** of material space requirements will be helpful. But in this case, planners need to know more than just the available site space and the quantity of site space required. They also need insight into the geometrical parameters of the individual material space requirements. Planners do not only want to know *that* the materials can be stored, they also want **to know where and how the materials can be stored.**

3.2 4D-CAD for construction logistics planning

The planning of construction logistics requires understanding of spatial and temporal relations and is thus a spatiotemporal problem. Since both space requirements as well as available space vary over time, planning the utilisation of space can be greatly facilitated by the use of 4D models (Akinci et al., 2000a).

A 4D model in this research will be defined as a model that integrates 3D geometry and the location of building components with timings of their construction. This graphical simulation of the sequence of construction operations allows planners to conduct various analyses prior to construction (Khanzode & Staub-French, 2007). This is another reason why the use of a 4D model will be helpful. It allows planners to plan the construction logistics prior to construction. This is important, as problems that are detected in this stage can still easily be dealt with earlier than in an ad hoc manner during construction.

3.2.1 Modelling time

Because material space requirement data will be used in a 4D environment, the modelling issues of time and material space requirements will need to be considered. In other words, are material space requirements to be quantified on an hourly, daily, weekly or even monthly basis? And how detailed does the representation of available space and required space need to be?

During material storage decisions, planners consider that every arrival and every use of a material either creates or removes a space requirement. This means that every arrival or removal (by use or otherwise) of a material, demarcates a time interval that requires a material storage decision. These time intervals are termed *primary time frames* (PTFs) (Zouein & Tommelein, 1999).

For material procurement decisions on the other hand, the timeframes that are analysed are not based on the activities that need materials, but on fixed order periods (FOPs).

In this research the aim is to support both material procurement and storage decisions. The timeframes wherein material space requirements need to be quantified, will therefore be defined in the same way as proposed by Said's and El-Rayes' Construction Logistics Planning method (Said & El-Rayes, 2010). In this method, the project is split up into stages. The timeframe that is analysed to

determine and quantify the material storage requirements, is the timeframe where the maximum inventory level is reached. The maximum inventory level is the largest quantity of material stored on site during the corresponding stage based on the order quantities of the FOPs.

Practical implication for the method:

To support this kind of decision making, a quantification of material space requirements is necessary **per task**, but also **per time unit** corresponding to the time units of the fixed order periods (e.g. day).

The QSRA Method will thus have to be able to add the space requirements of the materials of all tasks occurring on one day, to show the space requirements per day. And to show the space requirements per task, it will have to be able to add the space requirements of the materials of one task regardless of the duration of that task.

3.2.2 Modelling space

The time aspect described above is important for both material procurement and material storage decisions. Modelling the space aspect on the other hand is mainly important with regard to material storage decisions. In the case of material procurement decisions it is usually sufficient to use numerical volume data. This is not the case when it comes to material storage decisions, as geometrical information is needed because planners do not only want to know *that* the materials can be stored, but also *where* and *how*.

There are several methods for modelling available space and required space.

As for modelling *available* site space; in this research it is considered unwise to predefine the laydown areas as is done in the dynamic site layout method (Zouein & Tommelein, 1999), because this will limit the space where materials can be stored. This research will therefore assume that construction logistics planning uses a grid of locations like was done in facility layout planning (Mawdesley, Al-jibouri, & Yang, 2002). This method has shown to also be suitable for construction logistics planning (Said & El-Rayes, 2010).

As for modelling the *required* space, materials can be modelled using material footprints (Said & El-Rayes, 2010). To model these footprints in the 4D model, a method can be used that formalised the

representation of workspaces in a 4D environment (Akinci et al., 2000b). This method uses a generic representation of micro level spaces (e.g. equipment, hazard, protected areas) from an allocentric (inside/outside) perspective (see fig. 3). This representation method seems most suitable, as it provides a computer-interpretable way of capturing and representing space requirements.

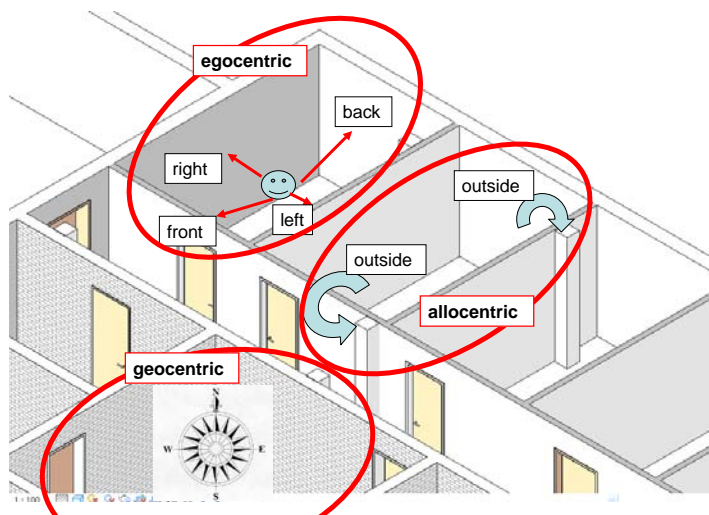


Figure 3: Egocentric, geocentric and allocentric representation

Akinci's method (2000b) defined three attributes that a generic space representation should have: (1) a reference object, (2) an orientation and (3) volumetric parameters.

Combining Akinci's generic representation with the above mentioned footprints (Said & El-Rayes, 2010) should give a good representation of materials in a 4D environment using (1) a reference object, (2) an orientation and (3) a footprint. Materials space requirements thus have to be quantified in such a way as to enable this representation method in 4D.

Practical implication for the method:

To enable a representation of the material space requirements in 4D, the material space requirements need to be represented not only on a **numerical value basis (e.g. m^2 , m^3)** but also on a **geometrical parameter basis (e.g. width, length, height)**. This will allow the identification of a footprint of a material space requirement, and also allow attribution of an orientation and a reference object to place it as a new object in a 4D model.

3.3 Quantifying material space requirements

As now the framework requirements for the QSRA-Method are described, the way to actually quantify material space requirements can be defined. The following theoretical points of departure were taken from an affiliated field of research: warehouse space planning research. This section will briefly explain the method used in warehouse space planning for quantifying material space requirements. In chapter 4 the adapted method for the construction industry will be presented.

In warehouse space planning, planners also have to quantify material space requirements for storage and procurement. To do so the following methodology is used (Tompkins & Smith, 1998):

1. Determine what is to be accomplished,
2. Determine what activities will take place to accomplish it,
3. Determine space allowances for each element required to accomplish the activity,
4. Calculate the total space requirements.

The actual quantification of the space requirement takes place in step 4 using a Storage Analysis Chart (SAC) of which two examples can be found in figure 4 (Kulwiec, 1985; Tompkins & Smith, 1998).

FACILITY DESIGN 661

Company _____ Date _____ Raw Materials _____ In-Process Goods _____
 Prepared by _____ Sheet _____ of _____ Plant Supplies _____ Finished Goods _____

Description	Unit Loads			Quantity of Unit Loads Stored			Storage Space				
	Type	Capacity	Size	Weight	Maximum	Average	Planned	Method	Specifications	Area (sq. ft.)	Ceiling Hgt. Req'd.
Aluminum rails, three runner 288"	Bundles	50 pcs.	18" x 28" x 288"	1250 lbs.	14	5	12	Cantilever rack	Four-arm dual rack, 4' x 12' x 6'	192	24
Glass, 1/4" thick, 8' x 4' sheets	Racks	4 sheets	8' x 4' x 4'	400 lbs.	20	13	15	Pallet rack	4' x 4' x 22' (4 levels)	240	24
Rubber Stripping 1/8" square	Cartons	500 feet	12" x 4" x 12"	20 lbs.	20	12	8	Industrial shelving	5 level 42" x 18" shelves	12	9
Adhesive, water sealant	Drum	350 lbs.	2' diameter x 4'	375 lbs.	7	3	6	Floor simple	2.5' x 2.0' floor loaded	60	8
Packing boxes 2' x 4' x 4"	Pallets	500	40" x 48" x 48"	600 lbs.	10	8	6	Bulk Stack	4' x 4' x 12' (3 levels)	80	15

what is stored *how much is stored* *how materials are to be stored*

Figure 4: Storage Analysis Charts

The information that the SAC tries to capture can be sorted into three predominant categories:

1. **What is stored**
physical characteristics of materials stored
2. **How much is stored**
quantities of materials stored
3. **How is it stored**
storage method and space required

The here described methodology was used as a starting point to build the QSRA-Method.

4 The QSRA-Method

The Quantitative Space Requirement Analysis Method (QSRA-Method) consists of three sub processes: (I) ‘**project analysis & recipe creation**’, (II) ‘**space requirement quantification**’ and (III) ‘**space requirement representation**’ (see QSRA-Method overview in fig. 5). The three subprocesses will be discussed separately in the next three sections of this chapter. Subprocess I (blue) corresponds to figure 6, subprocess II (green) corresponds to figure 8 and subprocess III (red) corresponds to figure 9. To represent the QSRA-Method the symbols of IBM flowcharting template X20-8020 conform ISO standard 5807 were used.

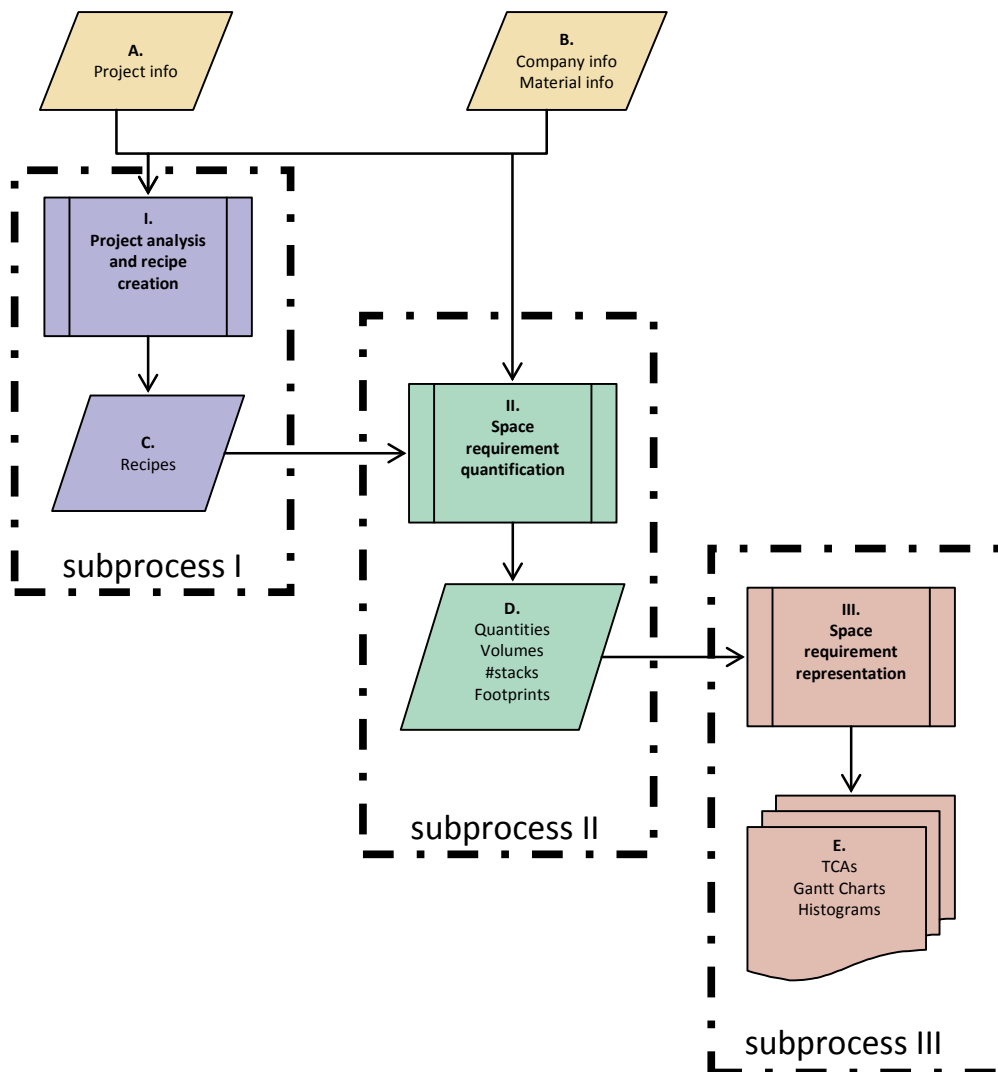


Figure 5: The QSRA-Method overview

Subprocess I helps planners analyse the project to determine *what* material space requirements need to be quantified. Furthermore, it helps planners create a method that shows *how* to quantify them.

The process resulted from combining step 1, 2 & 3 of Tompkins' & Smith's (1998) method for quantifying material space requirements in warehouse management (see previous section). The method was adapted to better suit the construction industry context.

Subprocess II of the QSRA-Method helps planners to transform material requirements into space requirements. This process relates to step 4 of Tompkins' & Smith's (1998) method: *calculating* the total space requirements.

Finally **subprocess III** resembles the Storage Analysis Chart (fig. 4) as used by Kulwiec (1985) and Tompkins & Smith (1998) for *representing* the space requirements (see previous section). The representation of the material space requirements is a separate process, because the material space requirements support two interdependent yet different decisions: material procurement and material storage decisions. These decisions require different information about the material space requirements (see section 3.1.1 & 3.1.2) and thus require different representations of the information. Apart from a representation method that is similar to the aforementioned SAC, two other representation methods are therefore offered to represent the material space requirement information. This will be further explained in the corresponding section 4.3.

4.1 Subprocess I: Project analysis & recipe creation

The first step in the QSRA-Method is called 'project analysis & recipe creation'. It is a process that identifies what types of materials are used on the project. To do so, it links material requirements to building objects. Then it accordingly creates a method (the recipes), that defines how to transform these types of materials into space requirements. The deliverable of this process is a method for quantifying material space requirements. More accurately: the recipes (output box C.II; fig. 6), which can be stored and reused for future projects. The recipes are created to allow the calculation of (1)

quantities to show how much materials are required. (2) The number of stacks to show how the quantities can be distributed over the available site space, and (3) the volumes & footprints to show how much space is required.

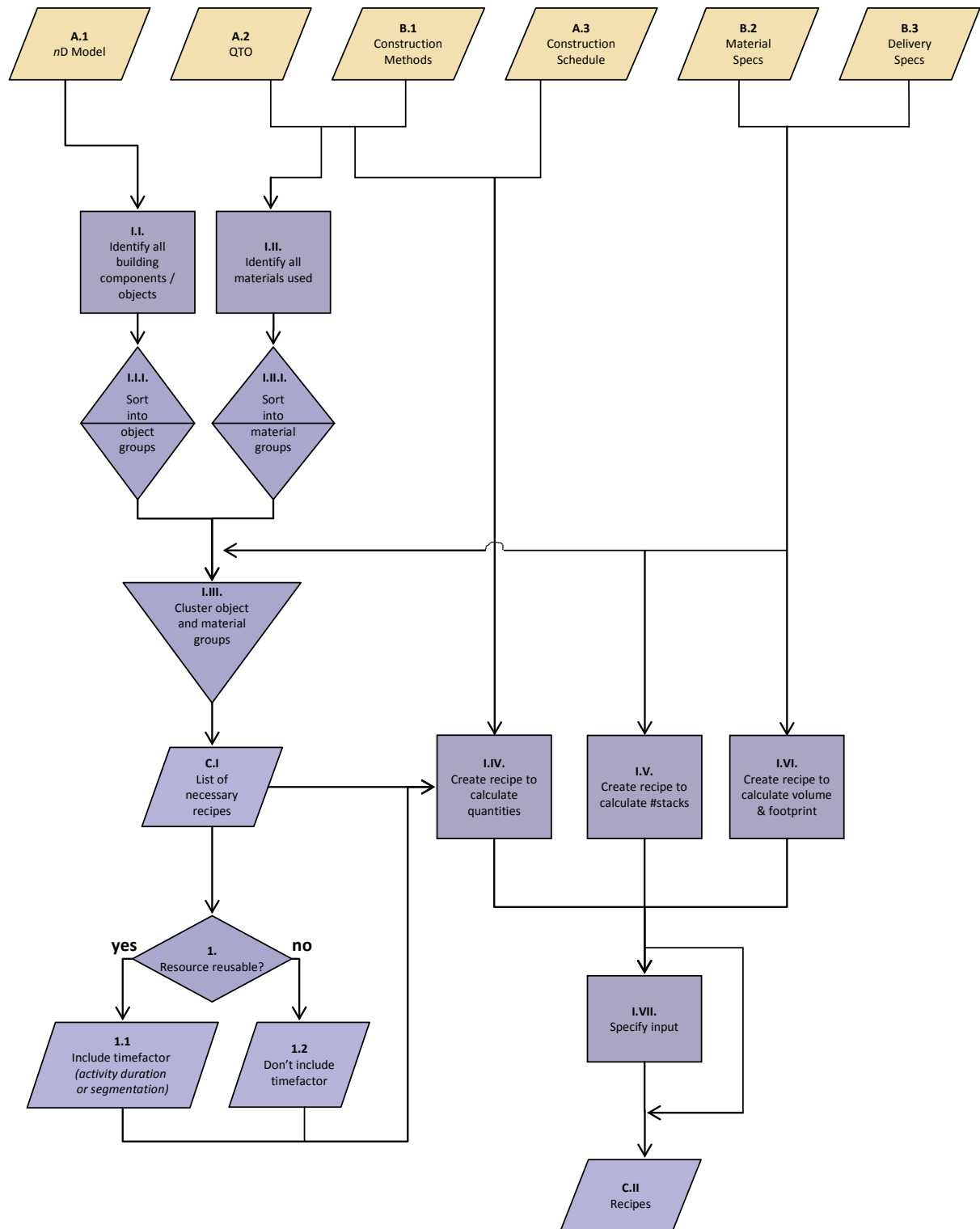


Figure 6: Project analysis & recipe creation (Subprocess I)

To create a method for quantifying material space requirements planners only need to know *what* materials are used. It does not matter at this point *when* or *where* the materials will be used. Therefore the input of subprocess I is a nD model (this can be a 2D/3D/4D model etc.).

To create the method for quantifying material space requirements (the recipes) the following steps are taken:

First, all building components (nD objects) of the nD Model are identified, listed and sorted into *object groups* (step I.I, fig. 6). Then the *material groups* are identified and listed (step I.II, fig. 6). These material groups consist of the materials that are used to create the objects in the object groups. For example ‘angular column’ is an object group, ‘formwork plates’ is a material group. The materials need to be identified separately, because they usually do not show up as objects in the nD model.

Then the object and material groups have to be clustered (step I.III, fig. 6). This link between object and material groups is necessary, because on the project the object information is available, material information is not. Since the material information is the information that is required, the created recipes will have to translate object information (the available information) into material information (the required information). Furthermore every object group is linked to several material groups, because the creation of one object usually requires several materials. This creates a list of object-material relations that shows which ‘material groups’ are necessary to create an object of a certain ‘object group’. This list is de facto the list of all necessary recipes that need to be created to quantify the material space requirements of the project.

So far, the process identified *what* recipes are necessary for transforming the objects in the nD model into material space requirements. Now the actual recipes have to be created using step I.IV to I.VI (fig. 6).

Step I.IV helps the planner create a sub-recipe to calculate quantities of material necessary for creating the objects in the object groups. First, the planner has to determine whether the material required is reusable (Question 1; fig. 6). If it is, the quantity of the material required will be time dependent.

After the planner has determined whether the quantity of the material needed is time dependent, the planner can create the sub-recipe. To do so, the planner will have to analyse (1) the construction method used, (2) the material specifications and (3) the delivery specifications. With the accumulated information the planner can now create a sub-recipe to transform 'project information' into 'quantities of materials necessary'.

Step I.V helps the planner create a sub-recipe for calculating 'the number of stacks of a material' in relation to 'the quantities of materials necessary'. The planner will need information about (1) the material specifications, (2) the stacking options of the material and (3) information about how the materials arrive on site.

Step I.VI helps planners create a sub-recipe to calculate the volume and footprint of the material as stored. The planner needs to create a sub-recipe that can transform information about 'the quantities of the material' and 'the number of stacks of the material' into volumes and footprints of the material. Here also the pathspace needs to be considered. On the storage area there needs to be room for aisles between the material stacks, otherwise the materials in the middle would be inaccessible. Also some materials require safety distances.

The need for creating a sub-recipe to calculate quantities (step I.IV) and a sub-recipe to calculate volumes and footprints (step I.VI) is quite self-explanatory. The necessity of creating a sub-recipe to calculate the number of stacks (step I.V) is less self-explanatory; the following two examples should clarify the need.

For storing decisions it might be crucial to know whether 20 m^3 (for example) are stored in 2 high or in 8 low stacks. Even though the volumetric space requirement (20 m^3) in this example stays the same, the storage space footprint on site will change.

Furthermore the number of stacks might increase the total volumetric space requirement as can be seen in the following example. Example 'Formwork: round columns' (fig. 7) shows that due to stacking options, additional elements in a stack might not have the same space requirements as the initial ones ($s > r$; fig. 7).

It becomes clear therefore that lower stacking heights will result in more elements with height 's' (the height of a first element in a stack) instead of 'r' (the height of an additional element in a stack). This means the stacking heights and the number of stacks can influence both the footprint as well as the total volumetric space required on site. For example 20 elements stored in 2 stacks will require $18*r + 2*s$ which requires less space (footprint- and volumetric-wise) than storing the 20 elements in 10 stacks which would require $10*r + 10*s$.

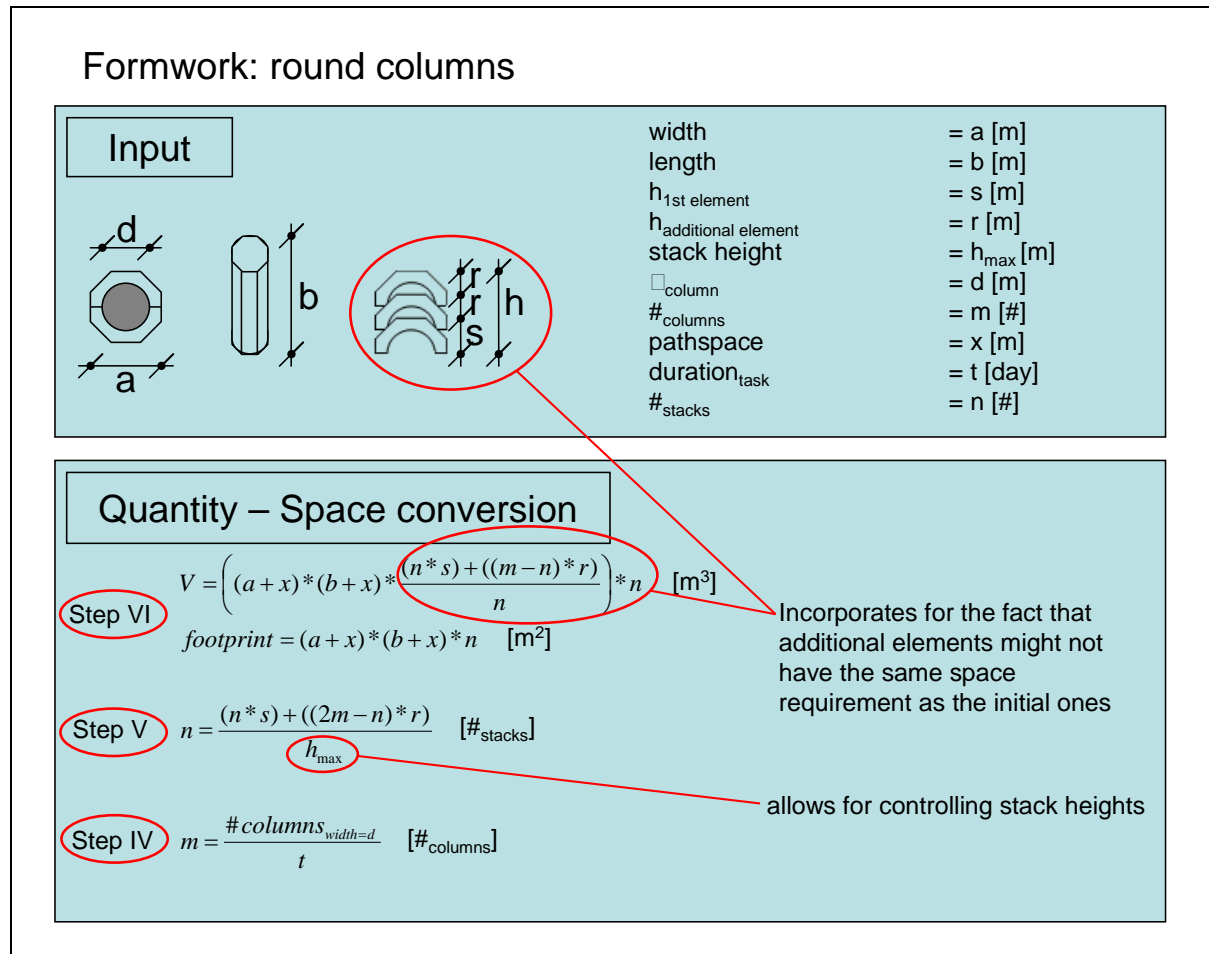


Figure 7: Example recipe *formwork, round columns*

Step I.V is furthermore important, because creating a recipe to calculate the number of stacks will allow the planner (who later on uses the recipe) to control stacking heights. This is necessary, because on some materials the manufacturer's specifications state a maximum stacking height due to the fragility of the material or the instability of stacks. Additionally, the planner can decide to not stack the material at all (i.e. because the material needs to be cleaned); in that case ' h_{max} ' will equal the height of the initial element. In this case: ' s '.

Step I.IV to I.VI will have to be conducted for all material-object group combinations that were identified and listed in step I.III. Then all recipes are created. This concludes subprocess I.

4.2 Subprocess II: Space requirement quantification

The second subprocess – space requirement quantification – is a process that uses the created recipes of subprocess I to *calculate* the required space. To do so the data as available from the project is first transformed according to the recipe input specifications. The deliverables of this process are (1) the quantities, (2) the volumes, (3) the number of stacks and (4) the footprints of materials per task (output box D.II – D.V; fig. 8).

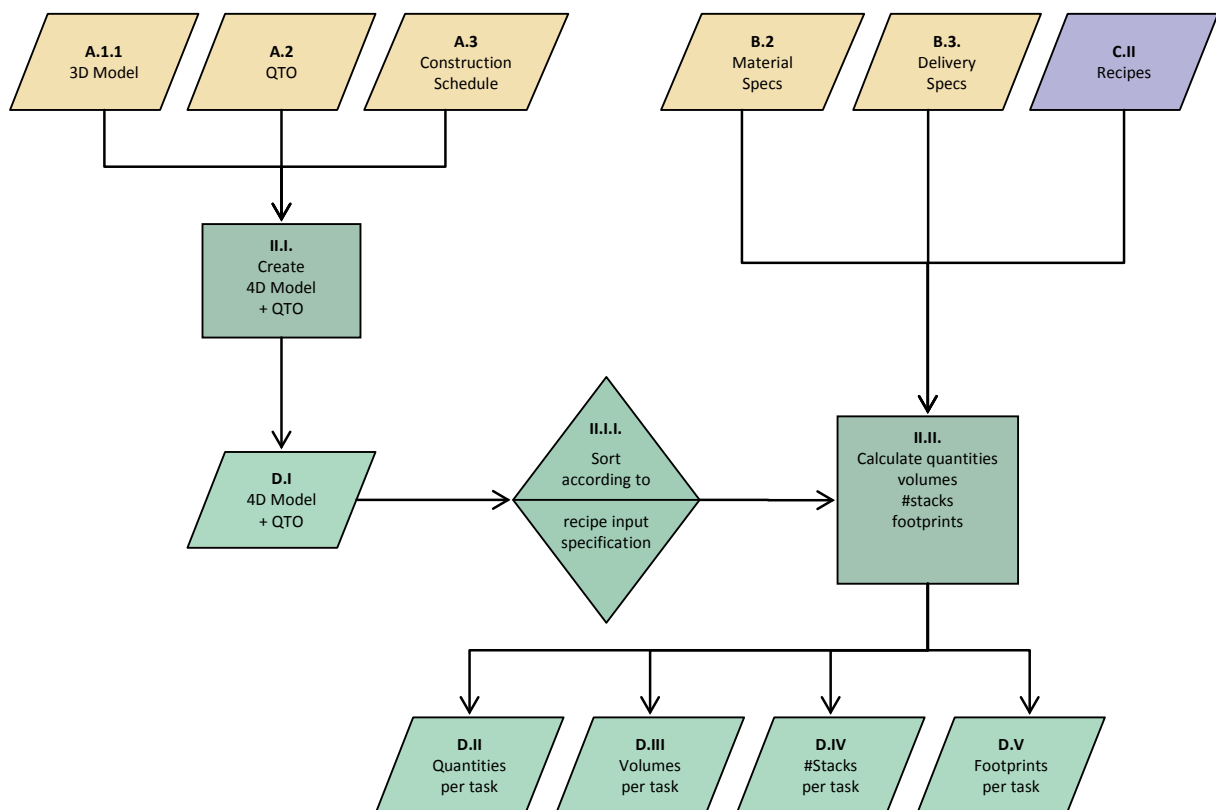


Figure 8: Space requirement quantification (Subprocess II)

For subprocess II it is necessary to know when and where materials are needed. Furthermore geometrical information of building components is required, thus a 3D and a 4D model are necessary. 2D models are not efficient enough to use as information source. Thus the term *n*D model does not apply in this section. This section distinguishes in 3D and 4D.

In step II.I the 3D model is linked to the schedule to create a 4D model. This will create insight into the spatiotemporal aspects of the material requirements. Additionally a QTO will have to be linked to

the 4D model. The QTO will query quantities from the 4D model that are necessary to calculate material space requirements (e.g. lateral surface area of the walls). The input specifications of the recipes will define which quantities have to be queried by the QTO.

The data received as output of the QTO-‘enriched’ 4D model can be stored in a data processing tool (e.g. Excel). The data still needs to be structured and sorted to better serve as input for the calculation process of the material space requirements (Step II.I.I). To sort and structure the data manually will take very long; hence it is advisable to create a VBA-application to do so.

After the project specific data has been sorted, the planner can use the recipes created in subprocess I to transform ‘project data’ into ‘material space requirement data’. Thus using the recipes, the planner can now calculate the material space requirements of the project and enter them in a data processing tool (e.g. Excel). This concludes subprocess II.

4.3 Subprocess III: Space requirement representation

The third subprocess – space requirement representation – is a process that helps planners represent the output of subprocess II to support decision making on material procurement and material storage (see section 3.1.1 & 3.1.2). The deliverables of this method are (1) a Gantt chart to show material space requirements per task, (2) a histogram to show material space requirements per time unit, and (3) a task-based space analysis chart (TSAC) to show geometrical information about the space requirements (see output box E.I – E.III; fig. 9).

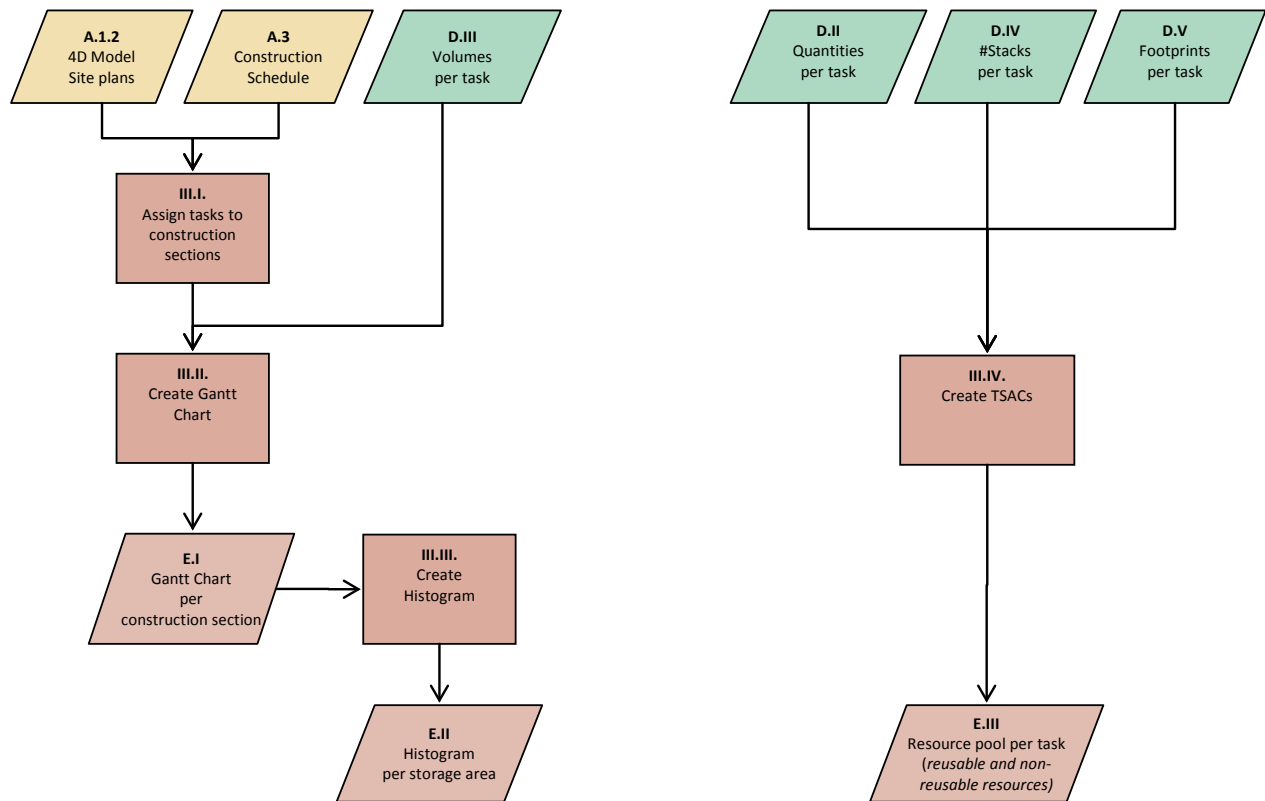


Figure 9: Space requirement representation (Subprocess III)

Planners want to represent space requirements on the lowest common denominator; which in construction practice is ‘the task’. Several tasks may be assigned to one object, but if one task is assigned to several objects, the task itself is split up in subtasks per object. This is because it is easier to split up a task than it is to split up an object. Thus space requirements are represented on task level.

Representing the material space requirements of the entire project in one graph will not provide enough detail and insight in the space requirements of a project. Representations therefore have to be made per section of the construction site. The sections can be defined on the basis of crane accessibility. The building components that are within the radius of a crane are defined as a construction section.

Segmenting the construction site in such a way is helpful, because materials between the axes of a so defined construction section will eventually¹ require space within this section. Hence these materials are usually stored within this construction section to minimise material handling.

Step III.I helps planners assign tasks to construction sections. In step III.II the volumes per task are added to the Gantt chart of the project and represented per construction section. This means one Gantt chart is made for every construction section. More accurately, the existing Gantt chart is dissected into Gantt charts per construction section.

Step III.III helps the planner create histograms per section of the construction site. The histogram can be created using the information of the Gantt chart E.I.

The histogram and the Gantt chart support material procurement planning and will also suffice for material storage planning in the tender phase of a project. The TSAC is to support material storage decisions after the tender phase of the project where planners need to decide *how* and *where* to store materials. As explained in the theoretical background (section 3.1.2), planners need insight into the geometrical parameters of the individual material space requirements in order to make material storage decisions.

As mentioned at the beginning of this chapter, the task-based space analysis chart (TSAC) relates to the Storage Analysis Chart (SAC, see fig. 4) as used by Kulwiec (1985) and Tompkins & Smith (1998). The three categories of information of the SAC (what, how much and how are materials stored) are used in the TSAC, complemented with information about *when* and *for how long* the materials are stored.

It should be denoted here that the created TSAC in fact represents material '**pool**' requirements per task. This is due to the fact that some materials (e.g. formwork) can be reused, and do not diminish due to execution of the task. Hence in order to execute a number of tasks, a pool of materials is

¹ Even if they were previously stored on another section, they will eventually have to be brought here to be built in.

required. Some of the materials (e.g. reinforcing) are taken from the pool and diminish due to the execution of the tasks, other materials (e.g. formwork) are used and put back into the pool. Ordering materials for one month instead of two weeks will therefore increase the amount of reinforcing that needs to be in the pool, but it won't necessarily increase the amount of formwork that needs to be in the pool.

Step III.IV, the TSAC, can be designed as an Excel-sheet that provides information about the quantities, the number of stacks and the footprints per task (see input of process III.IV, fig. 9 and for an example fig. 20). This concludes subprocess III, the representation of material space requirements.

5 Application of the QSRA-Method

The QSRA-Method as described in the previous section was applied on two example projects to show that the method is capable of generating the required material space requirement data in a real construction industry environment.

The method was first applied on the airport terminal project, because this project has a lot of materials. Thereafter the method was applied on the high-rise building, to show the reusability of the recipes.

The airport terminal project was the first project on which the QSRA-Method was used; hence the company did not yet have a database of recipes available. This means subprocess I 'project analysis & recipe creation' needed to be used to create a method (the recipes) to quantify the material space requirements for the materials and methods used by the company. On the second project, the high-rise building, the recipes of the airport terminal were reused. For the high-rise building project subprocess I could be skipped, thus this project started with subprocess II 'space requirement quantification'.

An additional note: The values in the examples shown are slightly adjusted to assure no company and project specific data is dispersed.

5.1 Subprocess I: Project analysis & recipe creation

Step I.I: In order to define what materials are required, it is necessary to know what building objects need to be constructed. Thus the 3D model of the airport was analysed and all building components were listed (e.g. angular columns 50x20, angular columns 20x30, walls 30cm, walls 50cm etc.).

Step I.I.I: The list of building components was sorted to make step I.III easier. All walls, slabs, columns etc. were listed sequentially in object groups (e.g. group walls, group slabs, etc.)

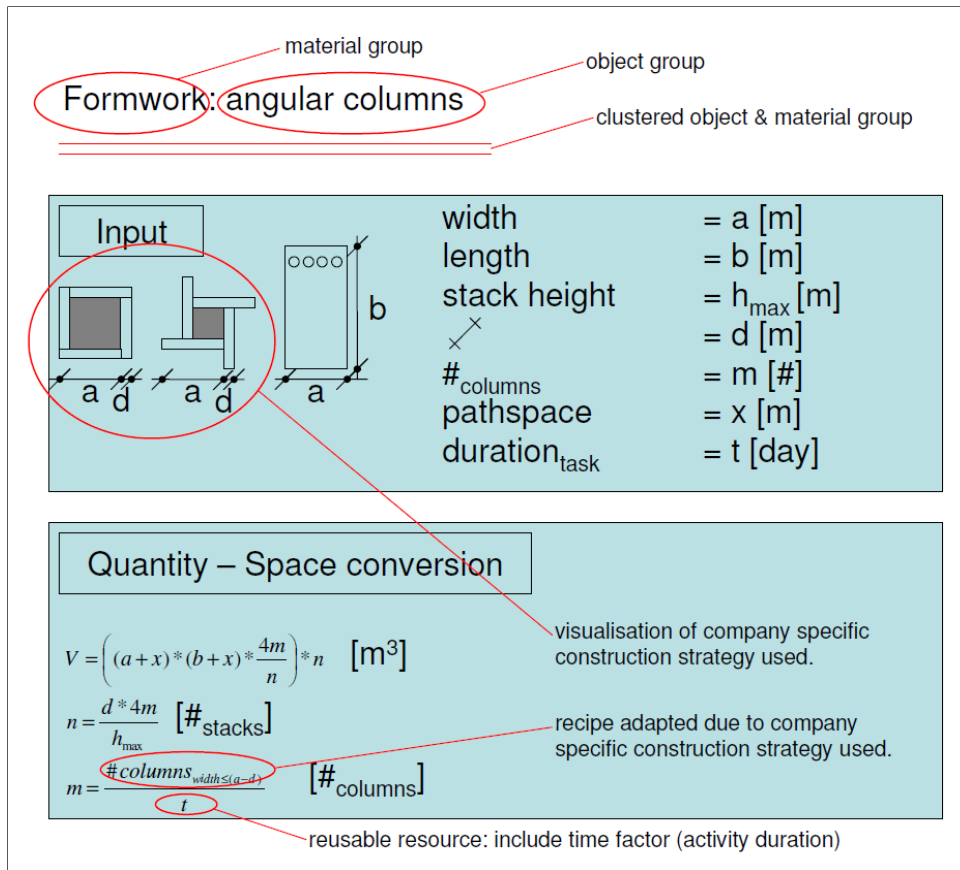
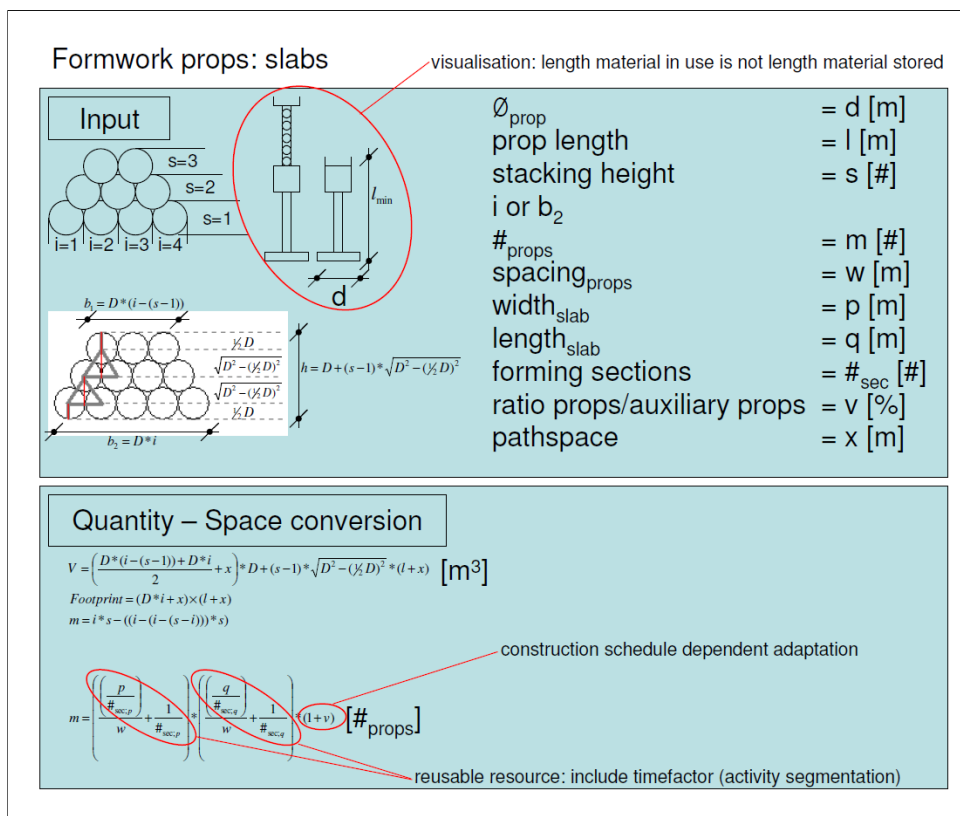
Step I.II: All materials necessary for creating the building components as identified in step I.I were listed. Some of the materials could be found in the bill of quantities, others where given as a

percentage of the 3D objects (e.g. reinforcing is 150 kg per cubic metre concrete), and some are construction method dependent. Thus the construction methods used for creating the building components were analysed. This was done by conducting interviews with construction planners and site managers.

Step I.II.I: Similar to step I.I.I, the materials (e.g. reinforcement stirrups, props, wall formwork plates etc.) were sorted and listed sequentially into material groups.

Step I.III: The link between ‘material groups’ and ‘object groups’ was created. This was done by creating a list of object-material relations that shows which ‘material groups’ are necessary to create the objects of an ‘object group’. E.g. the link between object group ‘angular columns’ and material groups ‘TRIO formwork plates’ and ‘reinforcing bars’ was created by putting object group ‘angular columns’ in the first column of a table and material groups ‘TRIO formwork plates’ and ‘reinforcing bars’ in the second column of the table. The resulting table was a list of all material-object group relations for which recipes had to be created.

The recipes of which the need was identified in step I.III were then created using step I.IV till I.VI. Two example recipes are shown below (see figs. 10&11). Figure 10 depicts the recipe for object group ‘angular column’, material group ‘formwork’. Figure 11 depicts the recipe for object group ‘slabs’, material group ‘formwork props’.

Figure 10: Example recipe *formwork, angular columns*Figure 11: Example recipe *formwork props, slabs*

Step 1.IV: The sub-recipes were created to calculate the quantities of material necessary. Semi-structured interviews with construction logistics planners and site managers were conducted to analyse the construction methods used by the company. This information combined with the knowledge about what data was available on the project (= available input data) was used to create the sub-recipes to calculate quantities.

In the ‘Formwork: angular column’ example, the sub-recipe is: $m = \frac{\#columns_{width \leq (a-d)}}{t}$. The material is reusable, thus question 1 indicates that a time factor needs to be included in the sub-recipe (See 1.1, fig. 6). After it is ascertained that the quantity is time dependent, the construction method will have to tell how the quantity of material required relates to time. In this case the quantity of formwork required, is dependent on the number of columns that are simultaneously formed. For example if 20 columns are formed in 5 days; the company specific construction policy defines that the formwork for 4 columns will suffice. This is an example of an ‘activity duration’ inclusion of a time factor.

Furthermore as this example shows, the company specific construction strategy can also influence the quantity of materials on a non time related basis. The company uses the same formwork for all columns up to width ‘a minus d’ (see fig. 10). A visualisation was added to ensure that the planner, who later on uses the recipe, interprets the company specific construction strategy correctly. Two columns are depicted: a big one and a slim one. As shown, the slim column simply has a little excess formwork.

In the ‘Formwork props: slabs’ example, the sub-recipe for calculating material quantities is:

$$m = \left(\left(\frac{p}{\#_{sec;p}} \right) + \frac{1}{\#_{sec;p}} \right) * \left(\left(\frac{q}{\#_{sec;q}} \right) + \frac{1}{\#_{sec;q}} \right) * (1 + v)$$

This example shows the inclusion of a '*segmentation based*' time factor. The material is reusable, thus question 1 indicates that a time factor needs to be included in the sub-recipe (See 1.1, fig. 6). The construction method defines, that the quantity of formwork required is dependent on the number of segments wherein the slab is created. If for example one slab is divided in four segments, only one fourth of the formwork is necessary.

As can be seen the sub-recipe allows for segmentation of both the width (p) as well as the length (q) of the slab. It also prevents the edge materials (the materials on the segmentation edges) to show up more than once due to segmentation.

Like the 'angular columns' example; the quantity of the material necessary is not only influenced by the fact that the material is reusable. This example too shows that a company specific construction strategy can influence the quantity of materials needed. Variable ' v ', the ratio of props/auxiliary props², is a construction-method-based and schedule-dependent rule of thumb. Variable ' v ' is an indirect indicator of how much (not how many!) 'slab forming tasks' overlap in the schedule. Since ' v ' is usually 1; ' v ' usually doubles the number of materials required and hence is very important.

Additionally, the example shows, that a visual representation should be incorporated to facilitate a correct interpretation of the recipe. In this case a visualisation of the material specifications was incorporated. The length of the prop clearly varies depending on whether it is in use or being stored (see fig. 11).

Step I.V: With the help of the already acquired information plus information on material and delivery specifications the sub-recipes to calculate the number of stacks of a material stored were created. In

² Auxiliary props are used to uphold the slab, after the formwork cross-beams and main-beams have been taken away. The cross-beams and main-beams can already be used to form the next slab, but the props need to stay in place for a few more weeks. The next slab of course also requires props, hence whilst simultaneously forming two or more slabs, auxiliary props are needed.

the 'Formwork: angular column' example, the sub-recipe is: $n = \frac{d \times 4m}{h_{\max}}$. Variable 'h_{max}' allows

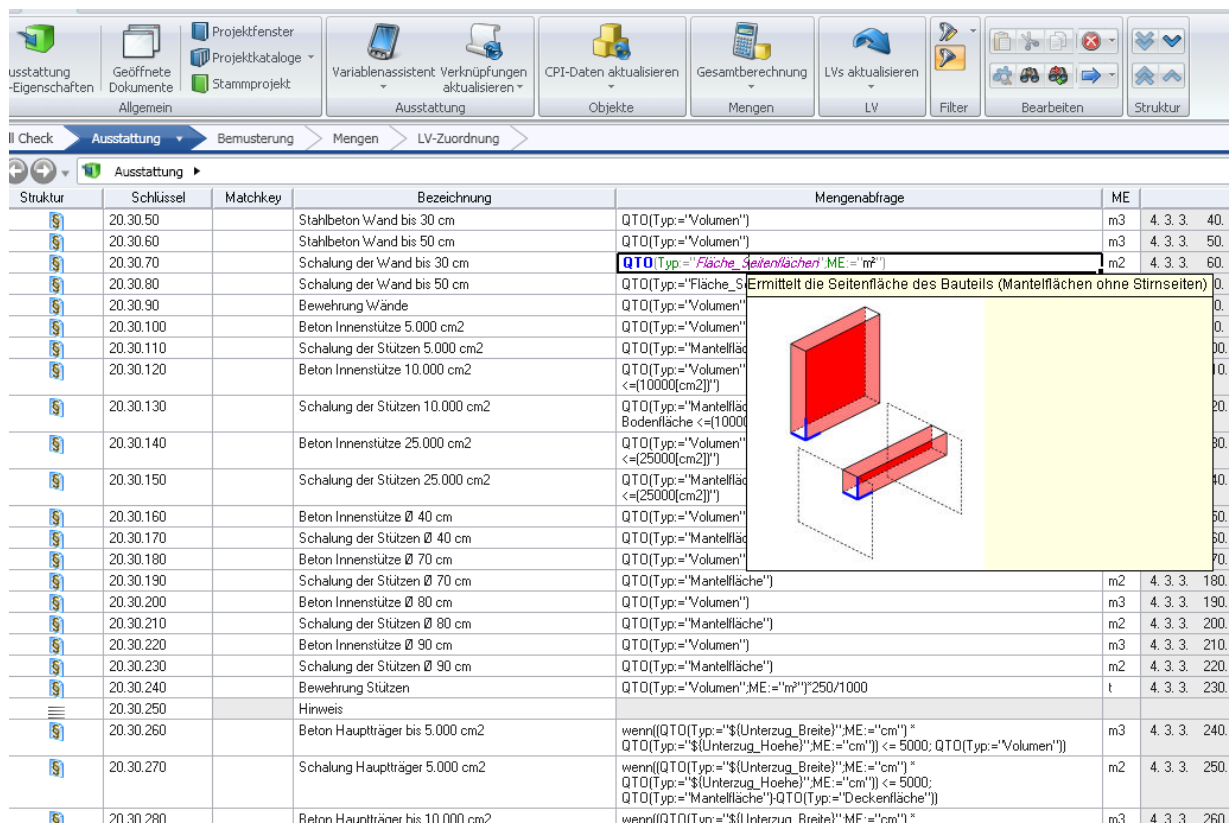
controlling stack-heights. And the 'd*4m'-term of the sub-recipe ensures that the formwork for one column is always stored together and not on separate stacks.

Step I.VI: Again using the already acquired information the sub-recipes were created to calculate the volume and footprint of the materials as stored. Here also the pathspace x was considered since there needs to be room for aisles and required safety distances. As advised by site managers, pathspace was assumed to be 0,6m.

The recipes created using step I.IV to I.VI can be found in the appendix. This concluded subprocess I.

5.2 Subprocess II: Space requirement quantification

Step II.I: The 3D model and schedule were linked to create a 4D model. Then QTO queries (see fig. 12) were created to query quantities from the 4D model. These were the quantities from the 4D model that were later on used as input to calculate material space requirements. In the example the lateral surface areas of the walls are queried.



Struktur	Schlüssel	Matchkey	Bezeichnung	Mengenabfrage	ME	
	20.30.50		Stahlbeton Wand bis 30 cm	QTO(Typ="Volumen")	m3	4.3.3. 40.
	20.30.60		Stahlbeton Wand bis 50 cm	QTO(Typ="Volumen")	m3	4.3.3. 50.
	20.30.70		Schalung der Wand bis 30 cm	QTO(Typ="Fläche, Seitenflächen", ME:="m²")	m2	4.3.3. 60.
	20.30.80		Schalung der Wand bis 50 cm	QTO(Typ="Fläche, Seitenflächen", ME:="m²")	m2	4.3.3. 60.
	20.30.90		Bewehrung Wände	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.100		Beton Innenstütze 5.000 cm2	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.110		Schalung der Stützen 5.000 cm2	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.120		Beton Innenstütze 10.000 cm2	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.130		Schalung der Stützen 10.000 cm2	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.140		Beton Innenstütze 25.000 cm2	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.150		Schalung der Stützen 25.000 cm2	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.160		Beton Innenstütze Ø 40 cm	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.170		Schalung der Stützen Ø 40 cm	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.180		Beton Innenstütze Ø 70 cm	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.190		Schalung der Stützen Ø 70 cm	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.200		Beton Innenstütze Ø 80 cm	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.210		Schalung der Stützen Ø 80 cm	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.220		Beton Innenstütze Ø 90 cm	QTO(Typ="Volumen")	m3	4.3.3. 60.
	20.30.230		Schalung der Stützen Ø 90 cm	QTO(Typ="Mantelfläche")	m2	4.3.3. 60.
	20.30.240		Bewehrung Stützen	QTO(Typ="Volumen", ME:="m³")/250/1000	t	4.3.3. 230.
	20.30.250		Hinweis			
	20.30.260		Beton Hauptträger bis 5.000 cm2	wenn(QTO(Typ="\$(Unterzug_Breite)", ME:="cm") * QTO(Typ="\$(Unterzug_Hoehe)", ME:="cm") <= 5000; QTO(Typ="Volumen"))	m3	4.3.3. 240.
	20.30.270		Schalung Hauptträger 5.000 cm2	wenn(QTO(Typ="\$(Unterzug_Breite)", ME:="cm") * QTO(Typ="\$(Unterzug_Hoehe)", ME:="cm") <= 5000; QTO(Typ="Mantelfläche")-QTO(Typ="Deckenfläche"))	m2	4.3.3. 250.
	20.30.280		Beton Hauptträger bis 10.000 cm2	wenn(QTO(Typ="\$(Unterzug_Breite)", ME:="cm") * QTO(Typ="\$(Unterzug_Hoehe)", ME:="cm") <= 10000; QTO(Typ="Volumen"))	m3	4.3.3. 260.

Figure 12: Screenshot: Example of a QTO query

The QTO-'enriched' 4D model is shown in figure 13.

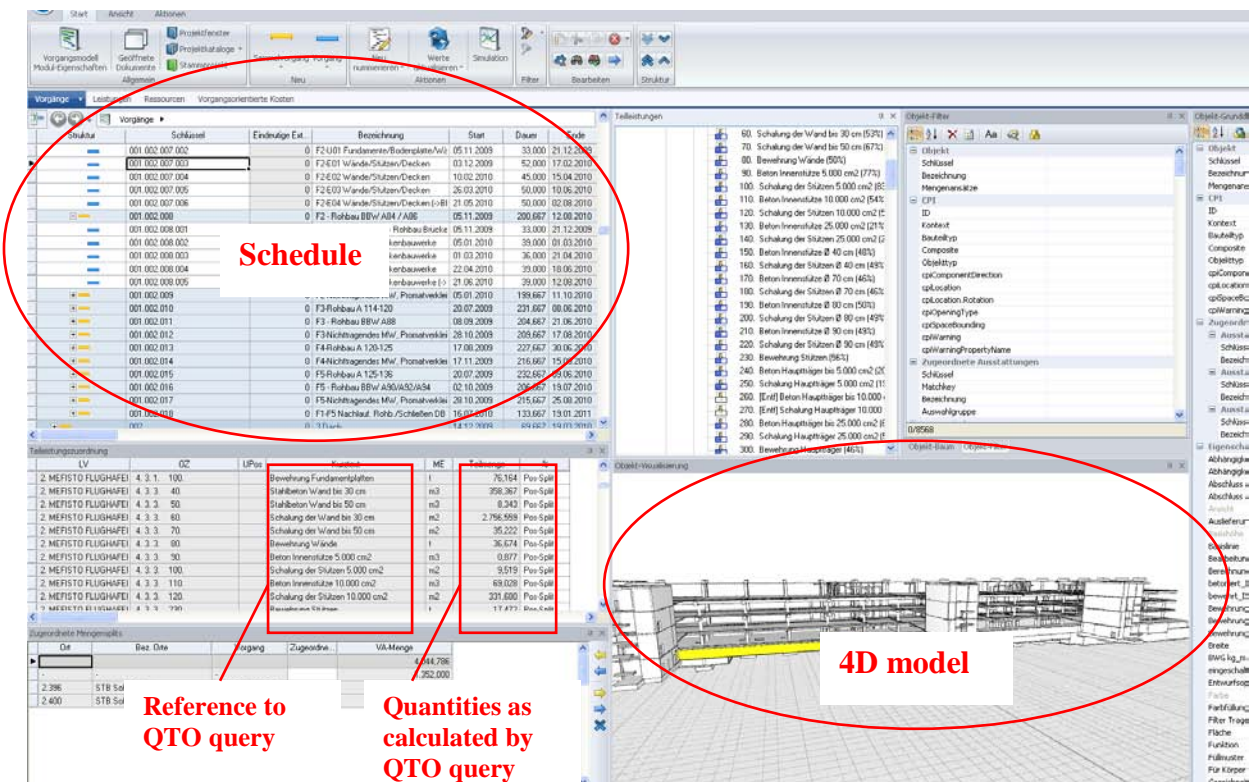


Figure 13: Screenshot: QTO-'enriched' 4D model

Step II.I: The data received as output of the QTO-‘enriched’ 4D model was stored in a data processing tool and structured to better serve as input for the recipes.

The output of the QTO-‘enriched’ 4D model uses a lot of sheets (see red frame fig. 14) because a new sheet is created for every main task. A main task is for example: ‘Structural work second floor between axes 75-111’.

24	2. ME 4. 3. 3. 230.	Bewehrung Stützen	t	23,202 Pos-Split		
25	2. ME 4. 3. 3. 730.	Beton Deckenplatten bis 30 cm	m3	72,593 Pos-Split		
26	2. ME 4. 3. 3. 740.	Schalung Deckenplatten bis 30 cm	m2	302,473 Pos-Split		
27	2. ME 4. 3. 3. 750.	Bewehrung Deckenplatten bis 30 cm	t	9,074 Pos-Split		
28	2. ME 4. 3. 3. 760.	Beton Deckenplatten bis 65 cm	m3	9,723 Pos-Split		
29	2. ME 4. 3. 3. 770.	Schalung Deckenplatten bis 65 cm	m2	28,408 Pos-Split		
30	2. ME 4. 3. 3. 780.	Bewehrung Deckenplatten bis 65 cm	t	1,216 Pos-Split		
31	2. ME 4. 3. 3. 910.	Ortbeton Podestplatten	m3	2,232 Pos-Split		
32	2. ME 4. 3. 3. 920.	Schalung Podestplatten	m2	8,199 Pos-Split		
33	2. ME 4. 3. 3. 930.	Bewehrung Podeste in Treppenhäusern	t	0,279 Pos-Split		
34	2. ME 4. 3. 3. 2070.	Beton Nebenträger bis 3.000 cm²	m3	0,39 Pos-Split		
35	2. ME 4. 3. 3. 2080.	Schalung Nebenträger bis 3.000 cm2	m2	4,42 Pos-Split		
36	2. ME 4. 3. 3. 2090.	Beton Nebenträger bis 6.000 cm²	m3	16,744 Pos-Split		
37	2. ME 4. 3. 3. 2100.	Schalung Nebenträger bis 6.000 cm2	m2	81,641 Pos-Split		
38		Bewehrung Nebenträger	t	2,99845		

Figure 14: Screenshot: Output of the QTO-‘enriched’ 4D model

Using a VBA the data was summarized and sorted onto the first sheet (see fig. 15).

					Object group reference									
Vorgang	Start	Dauer	Ende		Summe Fundament Schalung [m2]	Summe Fundament Bewehrung [t]	Summe Streifen Fundament Schalung [m2]	Summe Streifen Fundament Bewehrung [t]	Summe allgran Decken Schalung [m2]	Summe allgran Decken Bewehrung [t]	Summe Filigran Decken Schalung [m2]	Summe Filigran Decken Bewehrung [t]	Summe Decken Schalung [m2]	Summe Decken Bewehrung [t]
1.002.010.004	07.12.2009	49	16.02.2010		0,000	0,000	0,000	0,000	2672,750	34,460	15,261	1260,281	60,073	2074,621
1.002.013.004	06.01.2010	46	11.03.2010		0,000	0,000	0,000	0,000	1432,061	17,812	11,370	1137,702	59,402	2557,095
1.002.015.004	01.12.2009	49	10.02.2010		0,000	0,000	0,000	0,000	5087,490	66,001	13,595	1514,721	79,104	2930,197
1.002.004.005	12.01.2010	37	03.03.2010		0,000	0,000	0,000	0,000	2345,137	30,100	10,304	1011,662	52,607	2222,062
1.002.007.005	26.03.2010	50	10.06.2010		0,000	0,000	0,000	0,000	3679,250	47,813	12,375	823,630	81,338	2617,867
1.002.010.005	05.02.2010	46	13.04.2010		0,000	0,000	0,000	0,000	3442,917	43,962	14,301	1973,898	93,636	2695,627
1.002.013.005	22.02.2010	49	03.05.2010		0,000	0,000	0,000	0,000	2242,223	27,845	10,452	1429,809	70,243	2712,900
1.002.015.005	01.02.2010	49	12.04.2010		0,000	0,000	0,000	0,000	4815,332	62,880	12,375	1633,399	82,015	3671,422
1.002.004.006	11.02.2010	30	24.03.2010		0,000	0,000	0,000	0,000	1865,891	24,153	9,902	221,611	14,112	0,000
1.002.007.006	21.05.2010	50	02.08.2010		0,000	0,000	0,000	0,000	3546,672	51,165	16,589	950,547	21,041	0,000
1.002.010.006	24.03.2010	50	08.06.2010		0,000	0,000	0,000	0,000	3463,969	44,233	18,871	2080,138	136,758	462,747
1.002.013.006	16.04.2010	42	30.06.2010		0,000	0,000	0,000	0,000	2039,460	26,286	13,671	1400,272	80,902	476,198
1.002.015.006	29.03.2010	42	09.06.2010		0,000	0,000	0,000	0,000	6181,713	67,800	18,116	396,595	20,192	0,000

Figure 15: Screenshot: Summarized and sorted output of the QTO-‘enriched’ 4D model

Step II.II: Then the actual space requirements were calculated and stored in the data processing tool.

To gain insight in material and delivery specifications, catalogues were ordered from Doka (www.doka.com), Peri (www.peri.de), Baustahlgewebe (www.baustahlgewebe.com) and the results

(materials and delivery methods chosen) were discussed with construction planners to ensure realistic choices had been made. This concluded subprocess II.

5.3 Subprocess III: Space requirement representation

Step III.I: The first step of subprocess III was assigning tasks to construction sections. As explained in the previous chapter, the construction sections are defined on the basis of crane accessibility. As can be seen in figure 16, the radius of the cranes is already depicted on the site plans. Thus the axes that delineate the crane radius can be easily obtained. The construction schedule for both construction projects turned out to already have this segmentation included in the planning. Tasks were already sorted per axes-groups (axes 75-111, axes 111-126 etc.) and those axes corresponded to radii of the cranes.

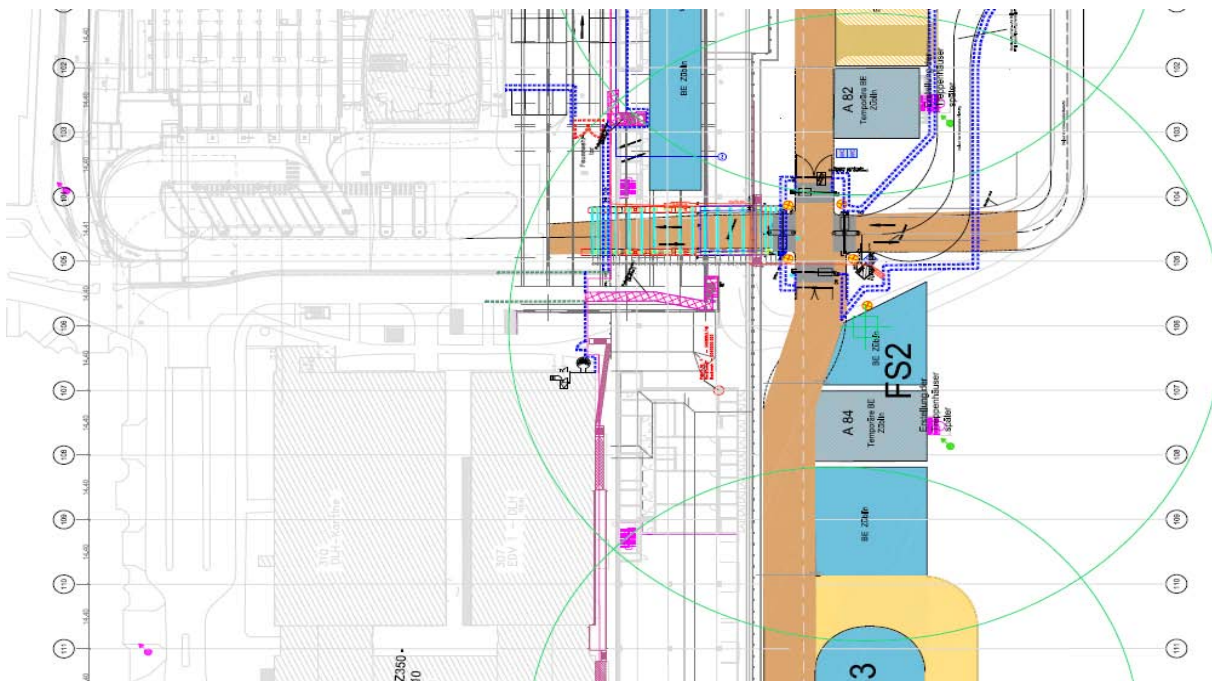


Figure 16: Crane radii (green) of the airport terminal

Step III.II: In step III.II the volumes as calculated in subprocess II were added to the Gantt chart per construction section (see figs. 17&18). First the Gantt chart of the project was split up in Gantt charts per construction section. Then the space requirements were added in the form of resources. The required space is thus treated as a resource that is being used by activities.

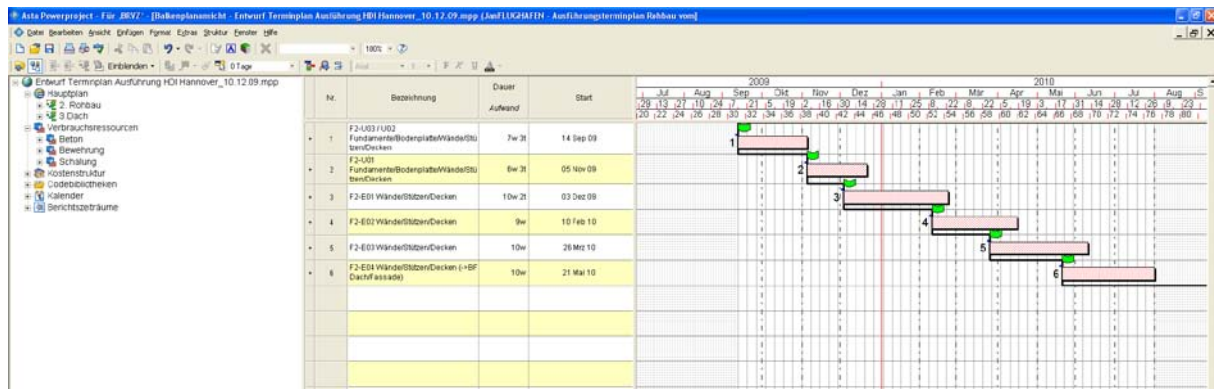


Figure 17: Screenshot: Section of the original Gantt chart of Axis 103-114 of the airport terminal

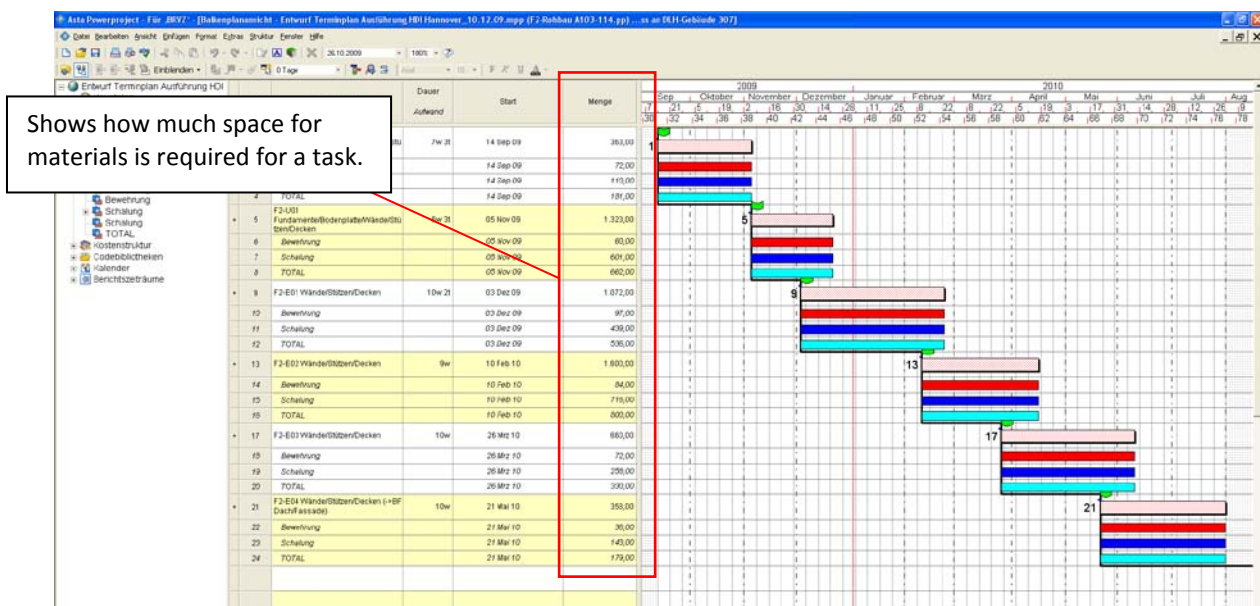


Figure 18: Screenshot: The same section of Axis 103-114 of the airport terminal with space requirements

Step III.III: Even though the scheduling tool itself is able to create histograms, the histograms were exported to the data processing tool. This was done, because the used data processing tool gives more options for manipulation and visualisation of the data, (see fig. 19).

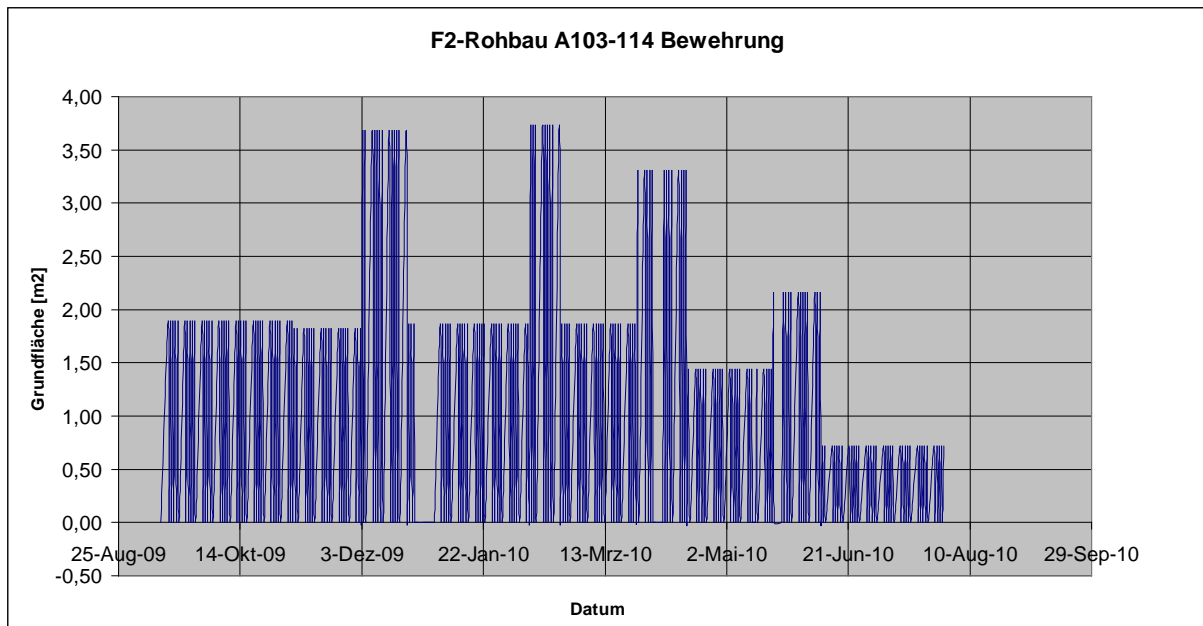


Figure 19: Screenshot: Space requirements of the reinforcing of Axis 103-114 of the airport terminal

The here depicted histogram shows the material space requirements in terms of footprints of *material stacks*³ in square metres.

Step III.IV: The material space requirements data (which was calculated in the data processing tool) could be easily restructured into a TSAC (fig. 20).

³ The footprints thus implicitly include stacking heights, number of stacks and pathspace.

B	C	D	E	F	G	H	I	J	K	L
1.002.010.004	07.12.2009	49	16.02.2010		0,000	0,000	0,000	0,000	2672,750	34,460
1.002.013.004	06.01.2010	46	11.03.2010		0,000	0,000	0,000	0,000	1432,081	17,812
1.002.015.004	01.12.2009	49	10.02.2010		0,000	0,000	0,000	0,000	5097,498	66,801
1.002.004.005	12.01.2010	37	03.03.2010		0,000	0,000	0,000	0,000	2345,137	30,180
1.002.007.005	26.03.2010	50	10.06.2010		0,000	0,000	0,000	0,000	3679,250	47,813
1.002.010.005	05.02.2010	46	13.04.2010		0,000	0,000	0,000	0,000	3442,917	43,962
1.002.013.005	22.02.2010	49	03.05.2010		0,000	0,000	0,000	0,000	2242,223	27,845
1.002.015.005	01.02.2010	49	12.04.2010		0,000	0,000	0,000	0,000	4815,332	62,880
1.002.004.006	11.02.2010	30	24.03.2010		0,000	0,000	0,000	0,000	1865,891	24,153
1.002.007.006	21.05.2010	50	02.08.2010		0,000	0,000	0,000	0,000	3946,672	51,165
1.002.010.006	24.03.2010	50	08.06.2010		0,000	0,000	0,000	0,000	3463,669	44,293
	15.04.2010	52	30.06.2010		0,000	0,000	0,000	0,000		6
	23.03.2010									0

Figure 20: Screenshot: Task-based storage analysis chart (TSAC)

5.4 Supporting decision making

This section gives an outlook on the way in which decision making can be supported by the quantified material space requirements. This is not part of the QSRA-Method anymore. This section serves to show that the output of the QSRA-Method meets the requirements of the decision processes as described in the theoretical points of departure. Future research endeavours will have to create tools and processes to show how the output of the QSRA-Method can be used to plan construction logistics.

The space requirements themselves are represented on a task level. In other words, we have the information on a level of detail where *primary time frames* (PTF; Zouein & Tommelein, 1999; see section 3.2.1) can be defined. The material space requirements of these PTFs can be clustered according to the *fixed order periods* (FOPs; Said & El-Rayes, 2010) using the histograms. The square metres needed for storing the materials of a fixed order period can be obtained by calculating the square metres of the time frame enclosed by the two consecutive FOPs (see figs. 21&22).

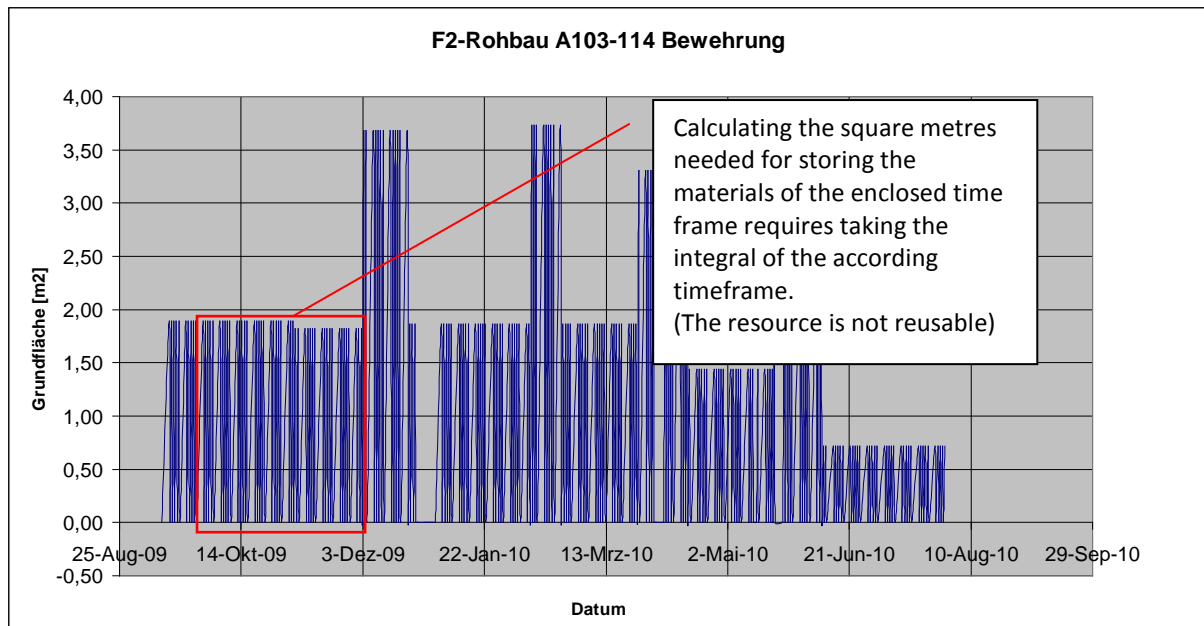


Figure 21: Space requirements of the reinforcing of Axis 103-114 of the airport terminal

The histograms depict the space requirements as needed per day by the tasks executed on that day. The way in which the histograms have to be read differs depending on whether the material is reusable or not (compare figs. 21&22). For non-reusable materials, the square metres needed are calculated by taking an integral of the enclosed time frame. For reusable materials, the maximum space requirement within the enclosed timeframe is taken.

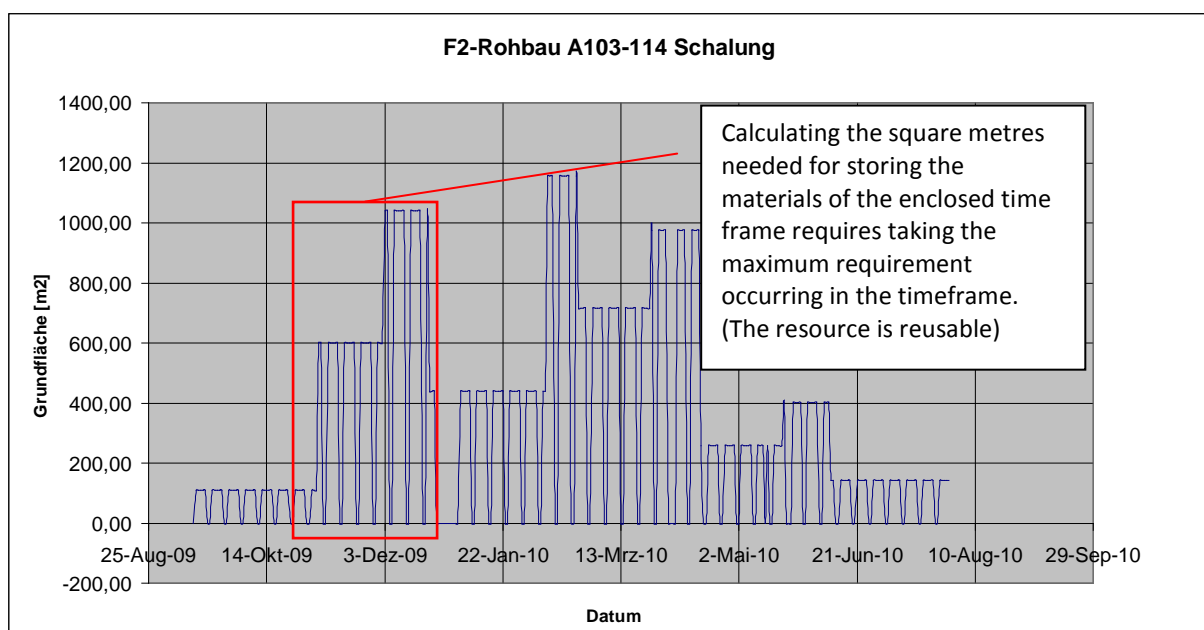


Figure 22: Space requirements of the formwork of Axis 103-114 of the airport terminal

Then the largest space requirement during the corresponding stage based on order quantities of the FOPs can be determined using the histogram and analysed (see section 3.2.1) using the Gantt chart.

The Gantt chart links the space requirements of a certain timeframe to the tasks of that timeframe.

If during a certain time period the space requirements exceed the amount of available space (this can be determined by analysing the histograms), the Gantt chart will help the planner determine which tasks contribute to the space demand. The Gantt chart will also show how much a certain activity contributes to the space demand as compared to other activities in the analysed timeframe.

Furthermore the footprints, the stack heights and the number of stacks of the material space requirements are represented per task in the TSAC. This will allow for a representation of materials in 4D using (1) a reference object, (2) an orientation and (3) a footprint and optionally a stack height (Akinci et al., 2000b; Said & El-Rayes, 2010; see section 3.2.2). This will allow for a visual analysis if necessary. The representation forms of the method thus should be able to support the decision processes as described in the theoretical points of departure. Creating the tools to do so is a task for future research endeavours.

6 Validation

6.1 Validation Method

The application of the method on the airport terminal and the high-rise building showed that the QSRA-Method was applicable on different construction projects and capable of producing recipes that were reusable.

The output of the QSRA-Method was validated using expert opinions. This was done, because the output of the QSRA-Method is in fact input for construction logistics planning. The research chose to not validate the QSRA-Method by actually planning construction logistics. This has several reasons. (1) There was no project data available to verify or compare the construction logistics plans. (2) Construction logistics plans made would not validate the output of the QSRA-Method, but rather the construction logistics planning methods. (3) Improvements in construction logistics would not be directly attributable to the QSRA-Method. (4) The output of planning construction logistics would be highly dependent on the expertise of the planner. Thus it was seen as the best option to inquire expert opinions on whether the input created by the QSRA-Method would be helpful.

6.2 Validation of the output of the QSRA-Method

The method and output of the QSRA-Method was shown to and discussed with a select group of construction planners and an IT specialist. The group was selected on the basis of knowledge of construction logistics planning and information modelling. The output of the QSRA-Method was appraised as helpful for construction logistic planning. In particular the histogram was perceived as valuable as it shows project information that traditional methods cannot.

One project manager pointed out that the way in which the recipes are created and depicted in the TSAC allows for analyzing the space requirements of materials during different processes. This would allow project planners to make spot checks whether there is enough space to execute certain activities. Formwork for example takes up more space when it is being cleaned than when it is being stored or built in. A spot check would allow a planner to check whether a planned activity 'cleaning of

slab-formwork' is possible on a certain storage location during an already congested time period. Whether the specified storage location is congested during a certain time period can be derived from the histogram.

The Gantt chart representation was considered helpful for analysing a detected material storage problem. A material storage problem means that the required space exceeds the available space. The Gantt chart will help planners determine which activities cause the required space of a certain time period that showed up in the histogram as being congested.

The TSAC was appraised as helpful for material storage decisions. Due to the fact that the TSAC represents the material space requirements not as single materials, but as stacks, the TSAC represents volumetric objects that can be placed on site. Since the TSAC already accounted for stacking options and stacking heights, the volumetric objects can be placed on site plans without further ado. This was seen as very helpful.

7 Discussion

As can now be concluded, the research goals (see introduction) are achieved. The QSRA-Method provides a method that enables planners to create recipes for quantifying material space requirements. This will ensure that not only existing materials can be quantified with the QSRA-Method, but also prospective ones.

Furthermore the method re-uses available project information and thus provides a time efficient alternative to existing methods. The majority of the processes of the QSRA-Method are created in such away as to be computer interpretable to allow future automation. This is highly recommended, because the analysis of the space requirements of materials is just one of many analyses that can be conducted on a construction project. In itself it solves just a small part of the space planning problem of a construction project.

The method however in itself is already helpful to support space planning efforts. It is capable of calculating and representing material space requirements per task, area and time unit. Furthermore the representation methods give planners insight into both the numerical space requirement in square metres, as well as the geometrical parameters of individual material space requirements.

Additionally the information provided in the TSAC allows planners to input the material space requirements as objects into a 4D model. This will facilitate storage decisions and virtual construction logistics simulations.

7.1 *Theoretical contributions*

The conducted research shows (1) the usefulness of 4D models in general in the construction industry and (2) in particular in construction logistics. (3) It provides a method for quantifying material space requirements and (4) shows what information is necessary as input. It (5) further highlights the interdependence of material procurement and storage and (6) provides insight into the practicality of integrally addressing these issues. Additionally the conducted research (7) links construction logistics with warehouse space planning research.

The conducted research shows the usability of a QTO-enriched 4D model to extract data for quantifying material space requirements on construction projects. It would have been difficult and probably not cost/time efficient enough to conduct the same analysis without the help of a 4D model. Without a 4D model, the information would have to be pieced together using 2D models, construction schedules and bills of quantities. This process is prone to error and very time consuming, because the information is stored in separate locations and formats. As opposed to traditional methods, the 4D model furthermore allows for a visual check to ensure the information has been pieced together properly. The research thus shows the usefulness of 4D models in the construction industry, and in particular the usefulness for construction logistics planning. The predominant amenities of the 4D models are that they help planners to *combine* and *extract* the necessary information for calculating material space requirements on construction projects.

Additionally, the method provided *quantifies* material space requirements instead of *estimating* them. This will contribute to construction logistics research, as it will help researchers gain more insight into actual space requirements of construction projects.

Another theoretical contribution of the research is that it shows what data are necessary in what level of detail and structure in order to plan construction logistics of materials on site.

Additionally, the interdependence of material procurement and storage decisions is shown. Combining these decision processes into construction logistics planning is relatively new. The here conducted research provides insight into the practicality of integrally addressing the issues by means of integrally creating the material space requirement information necessary for material procurement and storage.

Furthermore a link between ‘construction logistics planning research’ and ‘warehouse space planning research’ is established. This link will help future research endeavours find solutions for problems encountered in construction logistics planning.

7.2 *Practical implications*

From a practical standpoint this research will (1) aid planners to quantify material space requirements so as to plan construction logistics in the preconstruction phase of a project. (2) Give planners more insight into the space requirements of materials than traditional methods. (3) Support both material procurement as well as storage decisions. (4) Define the necessary input for the analysis. (5) Support other decision processes where material space requirement information is required. (6) Help Züblin in their efforts to create virtual construction logistics simulation tools. And (7) contribute to both the 5D Development Züblin as well as the Mefisto project.

As opposed to traditional methods, the QSRA-Method gives planners insight into the space requirements of materials per task and per time unit. It shows the relation between quantities and space requirements. And also the relation between stacking heights and space requirements. Additionally it shows their geometrical information and storage stacking options. This means that both material procurement as well as material storage decision making will be supported.

This research furthermore shows what data is necessary for the here proposed analysis and how other data creation processes can facilitate in creating and structuring the data for this analysis.

The output of the QSRA-Method can also be used to support other decision processes. The quantified material space requirements for example can be used as input for a detailed construction assembly simulation. Or they can be used for deciding what construction methods to use on the basis of the space required and space available for the respective method (E.g. Using 'In place concrete slabs' requires a method that takes up more material space than using 'filigran slabs').

Quantifying material space requirements can furthermore help in deciding how to schedule activities concurrently. For example: Forming five walls at the same time is no problem, cleaning the formwork of five walls at the same time on the other hand, takes up a large amount of space and might thus become critical. By quantifying as opposed to estimating material space requirements the QSRA-Method will increase the reliability of planning activities.

Furthermore this research will help Züblin in their efforts to create virtual construction logistics simulation tools. It will be a contribution to their work as a 5Di-partner as well as their work within the Mefisto project.

7.3 Limitations of the method

The accuracy of the output of the method is heavily dependent on the accuracy with which the 4D-model is created. That is to say, the method is dependent on how well a software program can interpret the data and link it together to calculate QTOs. If the 4D model is not properly modelled, a quantity takeoff calculation program will have trouble triangulating the surface areas and calculating volumes of building components. The limitation of the method is thus that it is dependent on a software program that can accurately calculate volumes and surface areas and is capable of properly adding⁴ those volumes and surface areas.

Furthermore the reliability of the calculated material space requirements is dependent on the proper creation and interpretation of the recipes. In an effort to overcome this, the recipes are accompanied by graphic visualisations (see fig 10&11). Still users of the QSRA-Method should be careful to avoid the created recipes from being multi-interpretable.

7.4 Further research suggestions

This research showed how the available information on a project can be transformed into material space requirement data. This information can now be used as input for decision support tools in construction planning.

Further research could be conducted on analysing how the output of the QSRA-Method can be used for construction assembly simulations. More specifically, how materials as quantified can be attributed to cranes, hoists etc. to determine whether cranes and hoists can handle the quantity and flow of materials on site. To do so the TSAC can be expanded with columns for weight and

⁴ The used tool had some problems with properly adding calculated areas and surfaces over multiple stories.

transportation methods as is done in warehouse space planning research (see RSAC, Receiving and Shipping Analysis Chart, Tompkins & Smith, 1998).

Since the QSRA-Method consists of quite a few steps, further research could be conducted to automate some of the steps of the method. Manually calculating the quantities is possible, but since the recipes are computer interpretable, automation would be useful.

Additionally, further research could show how to automatically transform the information in the TSAC into CAD-objects in the 4D-model. This would create an automated visualisation of the material space requirements of a project in 4D.

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Appendix

Foundations

Reinforcing bars foundations

Input

<input type="checkbox"/> bundle	= D [m]
<input type="checkbox"/> bar	= d [m]
bar length	= l [m]
stacking height	= s [#], h [m]
stacking width	= i [#], b ₂ [m]
# bundle	= m [#]
pathspace	= x [m]
reinforcement _{foundation}	= re _{foundation} [kg]
weight _{bundle}	= W _{bundle} [kg]
weight _{bar}	= W _{bar} [kg]
ratio stirrups/bars	= v

Quantity – Space conversion

$$V = \left(\frac{D * (i - (s-1)) + D * i}{2} + x \right) * D + (s-1) * \sqrt{D^2 - (\frac{D}{2})^2} * (l + x)$$

$$\text{Footprint} = (D * i + x) * (l + x)$$

$$m = i * s - ((i - (s-1))) * s$$

$$v = \frac{\text{stirrups} + \text{bars}}{\text{bars}}$$

$$m = \frac{\left(\frac{re_{\text{foundation}} [\text{kg}] * v}{W_{\text{bar}} [\text{kg}]} \right)}{\left(\frac{W_{\text{bundle}} [\text{kg}]}{W_{\text{bar}} [\text{kg}]} \right)}$$

Reinforcing stirrups column foundations

Input

<input type="checkbox"/> bundle	= D [m]
<input type="checkbox"/> stirrup	= d [m]
width	= a [m]
length	= b [m]
stack height	= h _{max} [m]
# bundle	= m [#]
pathspace	= x [m]
reinforcement _{foundation}	= re _{foundation} [kg]
weight _{bundle}	= W _{bundle} [kg]
weight _{stirrup}	= W _{stirrup} [kg]
ratio bars/stirrups/	= w

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \left(\frac{m}{2} * d \right) \right) * n$$

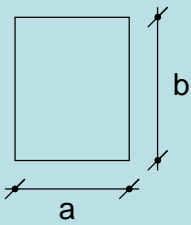
$$n = \frac{d * \frac{m}{2}}{h_{\text{max}}}$$

$$a = a_s + 2D; b = b_s + 2D$$

$$w = \frac{\text{stirrups} + \text{bars}}{\text{stirrups}}$$

$$m = \frac{\left(\frac{re_{\text{foundation}} [\text{kg}] * w}{W_{\text{stirrup}} [\text{kg}]} \right)}{\left(\frac{W_{\text{bundle}} [\text{kg}]}{W_{\text{stirrup}} [\text{kg}]} \right)}$$

Formwork: column foundations

Input	
	<p>width = a [m]</p> <p>length = b [m]</p> <p>stack height = h_{max} [m]</p> <p>x = d [m]</p> <p>foundation = A_{found} [m²]</p> <p>foundation = #_{found} [#]</p> <p>pathspace = x [m]</p> <p># formwork elements = m [#]</p> <p>duration_{task} = t [day]</p>

Quantity – Space conversion

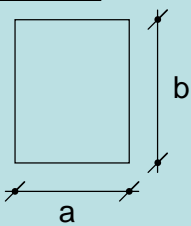
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{\left(\frac{A_{found}}{t} \right) + \frac{A_{found}}{\#_{found}} + \left(\frac{A_{found}}{t} \right) - \frac{A_{found}}{\#_{found}}}{a * b}$$

Formwork: strip foundations

Input	
	<p>width = a [m]</p> <p>length = b [m]</p> <p>stack height = h_{max} [m]</p> <p>x = d [m]</p> <p>foundation = A_{found} [m²]</p> <p>foundation = #_{found} [#]</p> <p>pathspace = x [m]</p> <p># formwork elements = m [#]</p> <p>duration_{task} = t [day]</p> <p>duration_{forming} = t_{form} [day]</p>

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

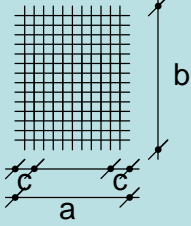
$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{\left(\frac{A_{found}}{t} \right) * t_{form}}{a * b}$$

Walls

Reinforcing bar mesh wall

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin-bottom: 10px;">Input</div> 	<table border="0"> <tr> <td>width</td> <td>= a [m]</td> </tr> <tr> <td>length</td> <td>= b [m]</td> </tr> <tr> <td>lap joint</td> <td>= c [m]</td> </tr> <tr> <td>stack height</td> <td>= h_{max} [m]</td> </tr> <tr> <td><input type="checkbox"/> reinforcing bar mesh</td> <td>= d [m]</td> </tr> <tr> <td># reinforcing bar mesh</td> <td>= m [#]</td> </tr> <tr> <td>pathspace</td> <td>= x [m]</td> </tr> <tr> <td>lateral surface_{wall}</td> <td>= A_{wall} [m²]</td> </tr> </table>	width	= a [m]	length	= b [m]	lap joint	= c [m]	stack height	= h _{max} [m]	<input type="checkbox"/> reinforcing bar mesh	= d [m]	# reinforcing bar mesh	= m [#]	pathspace	= x [m]	lateral surface _{wall}	= A _{wall} [m ²]
width	= a [m]																
length	= b [m]																
lap joint	= c [m]																
stack height	= h _{max} [m]																
<input type="checkbox"/> reinforcing bar mesh	= d [m]																
# reinforcing bar mesh	= m [#]																
pathspace	= x [m]																
lateral surface _{wall}	= A _{wall} [m ²]																

Quantity – Space conversion

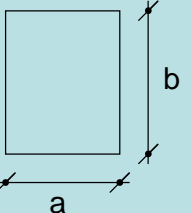
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{A_{wall}}{(a - c) * b}$$

Formwork: wall

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin-bottom: 10px;">Input</div> 	<table border="0"> <tr> <td>width</td> <td>= a [m]</td> </tr> <tr> <td>length</td> <td>= b [m]</td> </tr> <tr> <td>stack height</td> <td>= h_{max} [m]</td> </tr> <tr> <td><input checked="" type="checkbox"/> duration_{task}</td> <td>= t [day]</td> </tr> <tr> <td>pathspace</td> <td>= x [m]</td> </tr> <tr> <td>lateral area_{wall}</td> <td>= A_{wall} [m²]</td> </tr> <tr> <td>to be formed area</td> <td>= A_{form} [m²]</td> </tr> <tr> <td>pre forming ratio</td> <td>= v</td> </tr> </table>	width	= a [m]	length	= b [m]	stack height	= h _{max} [m]	<input checked="" type="checkbox"/> duration _{task}	= t [day]	pathspace	= x [m]	lateral area _{wall}	= A _{wall} [m ²]	to be formed area	= A _{form} [m ²]	pre forming ratio	= v
width	= a [m]																
length	= b [m]																
stack height	= h _{max} [m]																
<input checked="" type="checkbox"/> duration _{task}	= t [day]																
pathspace	= x [m]																
lateral area _{wall}	= A _{wall} [m ²]																
to be formed area	= A _{form} [m ²]																
pre forming ratio	= v																

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \left(\frac{\left(\frac{A_{form}}{a * b} \right) * d}{n} \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * \left(\frac{A_{form}}{a * b} \right)}{h_{max}}$$

$$A_{form} = \frac{A_{wall}}{t} * (v + 1)$$

Columns

Reinforcing bars columns

Input

\square_{bundle}	= D [m]
\square_{bar}	= d [m]
bar length	= l [m]
stacking height	= s [#], h [m]
stacking width	= i [#], b ₂ [m]
# _{bundle}	= m [#]
pathspace	= x [m]
reinforcement _{column}	= re _{column} [kg]
weight _{bundle}	= W _{bundle} [kg]
weight _{bar}	= W _{bar} [kg]

Quantity – Space conversion

$$V = \left(\frac{D * (i - (s - 1)) + D * i}{2} + x \right) * D + (s - 1) * \sqrt{D^2 - (\frac{1}{2}D)^2} * (l + x)$$

$$\text{Footprint} = (D * i + x) * (l + x)$$

$$m = i * s - ((i - (s - 1))) * s$$

$$m = \frac{\left(\frac{re_{\text{column}} [kg]}{W_{\text{bar}} [kg]} \right)}{\left(\frac{W_{\text{bundle}} [kg]}{W_{\text{bar}} [kg]} \right)}$$

Formwork: angular columns

Input

width	= a [m]
length	= b [m]
stack height	= h _{max} [m]
\times	= d [m]
# _{columns}	= m [#]
pathspace	= x [m]
duration _{task}	= t [day]

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \frac{4m}{n} \right) * n$$

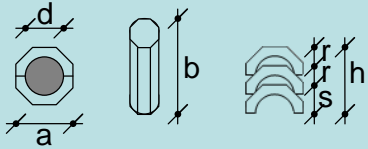
$$\text{footprint} = (a + x) * (b + x) * n$$

$$n = \frac{d * 4m}{h_{\text{max}}}$$

$$m = \frac{\# \text{columns}_{\text{width} \leq (a-d)}}{t}$$

Formwork: round columns

Input



width

length

$h_{1st\ element}$

$h_{additional\ element}$

stack height

\square_{column}

$\#_{columns}$

pathspace

$duration_{task}$

$\#_{stacks}$

= a [m]

= b [m]

= s [m]

= r [m]

= h_{max} [m]

= d [m]

= m [#]

= x [m]

= t [day]

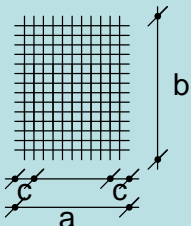
= n [#]

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \frac{(n * s) + ((m - n) * r)}{n} \right) * n$$
$$footprint = (a + x) * (b + x) * n$$
$$n = \frac{(n * s) + ((2m - n) * r)}{h_{max}}$$
$$m = \frac{\#_{columns_{width=d}}}{t}$$

Slabs – In place concrete

Reinforcing bar mesh slabs

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin-bottom: 10px;">Input</div> 	<p>width = a [m] length = b [m] lap joint = c [m] stack height = h_{max} [m] <input type="checkbox"/> reinforcing bar mesh = d [m] # reinforcing bar mesh = m [#] pathspace = x [m] slab = A_{slab} [m²]</p>
--	--

Quantity – Space conversion

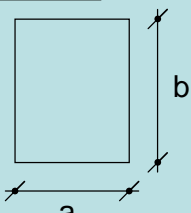
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{A_{slab}}{(a - c) * b}$$

Formwork: slabs

<div style="border: 1px solid black; padding: 5px; width: fit-content; margin-bottom: 10px;">Input</div> 	<p>width = a [m] length = b [m] stack height = h_{max} [m] x = d [m] slab = A_{slab} [m²] forming segments = #_{seg} [#] pathspace = x [m] # formwork elements = m [#]</p>
--	--

Quantity – Space conversion

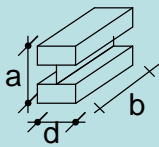
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{\left(\frac{A_{slab}}{\#_{seg}} \right)}{a * b}$$

Formwork: cross beams slabs

<div style="border: 1px solid black; padding: 5px; display: inline-block;">Input</div> 	width	= a [m]
	length	= b [m]
	lap joint	= c [m]
	stack height	= h _{max} [m]
	\times	= d [m]
	# _{cross beams}	= m [#]
	spacing _{cross beams}	= f [m]
	length _{slab}	= p [m]
	width _{slab}	= q [m]
	forming sections	= # _{sec} [#]
	pathspace	= x [m]

Quantity – Space conversion

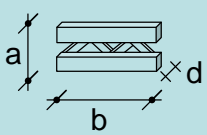
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \left(\frac{\left(\frac{p}{\#_{sec;p}} \right) + \frac{1}{\#_{sec;p}}}{f} * \left(\frac{q}{b - c} \right) \right)$$

Formwork: main beams slabs

<div style="border: 1px solid black; padding: 5px; display: inline-block;">Input</div> 	width	= a [m]
	length	= b [m]
	lap joint	= c [m]
	stack height	= h _{max} [m]
	\times	= d [m]
	# _{main beams}	= m [#]
	spacing _{main beams}	= k [m]
	length _{slab}	= p [m]
	width _{slab}	= q [m]
	forming sections	= # _{sec} [#]
	pathspace	= x [m]

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \left(\frac{\left(\frac{p}{\#_{sec;p}} \right) + \frac{1}{\#_{sec;p}}}{b - c} * \left(\frac{q}{k} + \frac{1}{\#_{sec;q}} \right) \right)$$

Formwork: props slabs

Input

\square_{prop}	= d [m]
prop length	= l [m]
stacking height	= s [#]
i or b ₂	
# _{props}	= m [#]
spacing _{props}	= w [m]
width _{slab}	= p [m]
length _{slab}	= q [m]
forming sections	= # _{sec} [#]
ratio props/auxiliary props	= v [%]
pathspace	= x [m]

Quantity – Space conversion

$$V = \left(\frac{D * (i - (s - 1)) + D * i}{2} + x \right) * D + (s - 1) * \sqrt{D^2 - \left(\frac{1}{2}D\right)^2} * (l + x)$$

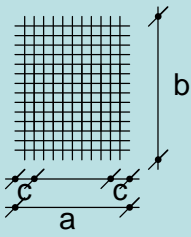
Footprint = (D * i + x) * (l + x)

m = i * s - ((i - (s - i))) * s

$$m = \left(\left(\frac{p}{\#_{\text{sec},p}} \right) + \frac{1}{\#_{\text{sec},p}} \right) * \left(\left(\frac{q}{\#_{\text{sec},q}} \right) + \frac{1}{\#_{\text{sec},q}} \right) * (1 + v)$$

Slabs – Filigran slabs

Reinforcing bar mesh filigran slabs

<div style="border: 1px solid black; padding: 2px; display: inline-block;">Input</div> 	<table border="0"> <tr><td>width</td><td>= a [m]</td></tr> <tr><td>length</td><td>= b [m]</td></tr> <tr><td>lap joint</td><td>= c [m]</td></tr> <tr><td>stack height</td><td>= h_{max} [m]</td></tr> <tr><td><input type="checkbox"/> reinforcing bar mesh</td><td>= d [m]</td></tr> <tr><td># reinforcing bar mesh</td><td>= m [#]</td></tr> <tr><td>pathspace</td><td>= x [m]</td></tr> <tr><td>slab</td><td>= A_{slab} [m²]</td></tr> </table>	width	= a [m]	length	= b [m]	lap joint	= c [m]	stack height	= h _{max} [m]	<input type="checkbox"/> reinforcing bar mesh	= d [m]	# reinforcing bar mesh	= m [#]	pathspace	= x [m]	slab	= A _{slab} [m ²]
width	= a [m]																
length	= b [m]																
lap joint	= c [m]																
stack height	= h _{max} [m]																
<input type="checkbox"/> reinforcing bar mesh	= d [m]																
# reinforcing bar mesh	= m [#]																
pathspace	= x [m]																
slab	= A _{slab} [m ²]																

Quantity – Space conversion

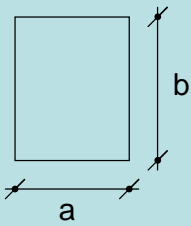
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{A_{slab}}{(a - c) * b}$$

Formwork: filigran slabs

<div style="border: 1px solid black; padding: 2px; display: inline-block;">Input</div> 	<table border="0"> <tr><td>width</td><td>= a [m]</td></tr> <tr><td>length</td><td>= b [m]</td></tr> <tr><td>stack height</td><td>= h_{max} [m]</td></tr> <tr><td>x</td><td>= d [m]</td></tr> <tr><td>slab</td><td>= A_{slab} [m²]</td></tr> <tr><td>forming segments</td><td>= #_{seg} [#]</td></tr> <tr><td>pathspace</td><td>= x [m]</td></tr> <tr><td># formwork elements</td><td>= m [#]</td></tr> </table>	width	= a [m]	length	= b [m]	stack height	= h _{max} [m]	x	= d [m]	slab	= A _{slab} [m ²]	forming segments	= # _{seg} [#]	pathspace	= x [m]	# formwork elements	= m [#]
width	= a [m]																
length	= b [m]																
stack height	= h _{max} [m]																
x	= d [m]																
slab	= A _{slab} [m ²]																
forming segments	= # _{seg} [#]																
pathspace	= x [m]																
# formwork elements	= m [#]																

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{\left(\frac{A_{slab}}{\#_{seg}} \right)}{a * b}$$

Formwork: props filigran slabs

Input

Diagram illustrating the input parameters for the formwork calculation, including prop spacing (s=1, s=2, s=3), prop indices (i=1, i=2, i=3, i=4), and the resulting slab width (b₁ = D * i) and height (h = D + (s-1) * √(D² - (1/2 D)²)).

□ _{prop}	= d [m]
prop length	= l [m]
stacking height	= s [#]
i or b ₂	
# _{props}	= m [#]
spacing _{props}	= w [m]
width _{slab}	= p [m]
length _{slab}	= q [m]
forming sections	= # _{sec} [#]
ratio props/auxiliary props	= v [%]
pathspace	= x [m]

Quantity – Space conversion

$$V = \left(\frac{D * (i - (s-1)) + D * i}{2} + x \right) * D + (s-1) * \sqrt{D^2 - (1/2 D)^2} * (l + x)$$

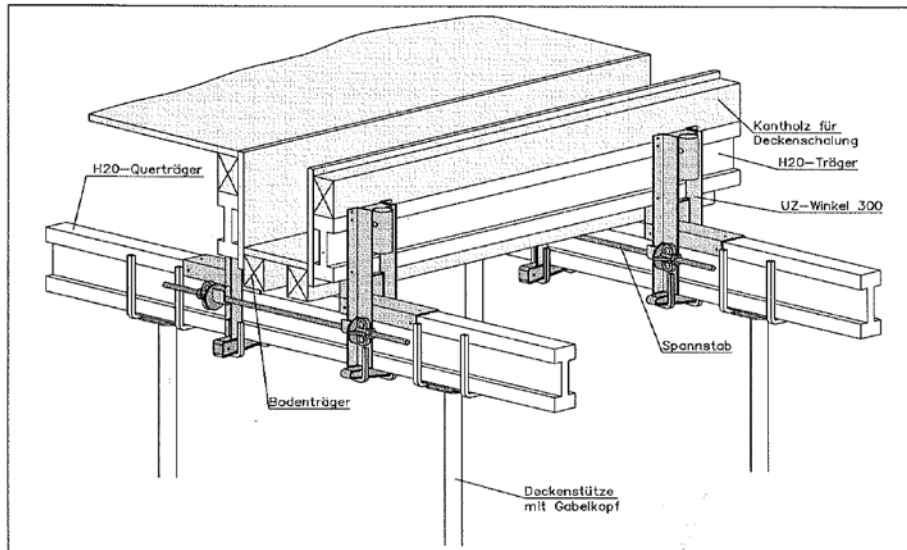
Footprint = (D * i + x) * (l + x)

m = i * s - ((i - (s-1))) * s

$$m = \left(\left(\frac{p}{\#_{sec,p}} \right) + \frac{1}{\#_{sec,p}} \right) * \left(\left(\frac{q}{\#_{sec,q}} \right) + \frac{1}{\#_{sec,q}} \right) * (1 + v)$$

Beams

NOE H 20 Unterzugs-Schalung eine sichere Investition



Reinforcing stirrups beams

Input	
	<ul style="list-style-type: none"> <input type="checkbox"/> bundle <input type="checkbox"/> stirrup width length stack height #_bundle pathspace reinforcement_{beams} weight_{bundle} weight_{stirrup} ratio stirrups/bars
	<ul style="list-style-type: none"> = D [m] = d [m] = a [m] = b [m] = h_{max} [m] = m [#] = x [m] = re_{beams} [kg] = W_{bundle} [kg] = W_{stirrup} [kg] = v

Quantity – Space conversion

$$V = \left((a+x) * (b+x) * \left(\frac{m}{2} * d \right) \right) * n$$

$$\text{footprint} = (a+x) * (b+x) * n$$

$$n = \frac{d * \frac{m}{2}}{h_{\max}}$$

$$a = a_s + 2D; b = b_s + 2D$$

$$v = \frac{\text{stirrups} + \text{bars}}{\text{stirrups}}$$

$$m = \frac{\left(\frac{re_{\text{beams}} [\text{kg}] * v}{W_{\text{stirrup}} [\text{kg}]} \right)}{\left(\frac{W_{\text{bundle}} [\text{kg}]}{W_{\text{stirrup}} [\text{kg}]} \right)}$$

Reinforcing bars beams

Input

<input type="checkbox"/> bundle	= D [m]
<input type="checkbox"/> bar	= d [m]
bar length	= l [m]
stacking height	= s [#], h [m]
stacking width	= i [#], b ₂ [m]
# bundle	= m [#]
pathspace	= x [m]
reinforcement _{beams}	= re _{beams} [kg]
weight _{bundle}	= W _{bundle} [kg]
weight _{bar}	= W _{bar} [kg]
ratio stirrups/bars	= v

Quantity – Space conversion

$$V = \left(\frac{D * (i - (s-1)) + D * i}{2} + x \right) * D + (s-1) * \sqrt{D^2 - \left(\frac{D}{2}\right)^2} * (l + x)$$

$$Footprint = (D * i + x) * (l + x)$$

$$m = i * s - ((i - (s-1))) * s$$

$$v = \frac{stirrups + bars}{bars}$$

$$m = \frac{\left(\frac{re_{beams} [kg] * v}{W_{bar} [kg]} \right)}{\left(\frac{W_{bundle} [kg]}{W_{bar} [kg]} \right)}$$

Formwork: Beams

Input

width	= a [m]
length	= b [m]
stack height	= h _{max} [m]
<input type="checkbox"/>	= d [m]
lateral area _{beam}	= A _{beam} [m ²]
pathspace	= x [m]
# formwork elements	= m [#]

Quantity – Space conversion

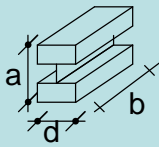
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{\left(\frac{A_{beam} - A_{topsurface}}{\#_{seg}} \right)}{a * b}$$

Formwork: main form beams; beams

Input		
	width	= a [m]
	length	= b [m]
	stack height	= h _{max} [m]
	\times	= d [m]
	# _{main beams}	= m [#]
	length _{beam}	= l [m]
	lateral area _{beam}	= A _{beam} [m ²]
	forming sections	= # _{sec} [#]
	pathspace	= x [m]

Quantity – Space conversion

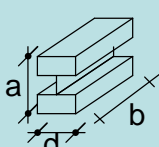
$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \frac{\left(\frac{A_{beam} - A_{topsurface}}{\#_{seg}} \right)}{a * b}$$

Formwork: cross form beams; beams

Input		
	width	= a [m]
	length	= b [m]
	stack height	= h _{max} [m]
	\times	= d [m]
	# _{cross beams}	= m [#]
	length _{beam}	= l [m]
	spacing _{cross beams}	= k [m]
	forming sections	= # _{sec} [#]
	pathspace	= x [m]

Quantity – Space conversion

$$V = \left((a + x) * (b + x) * \left(\frac{m}{n} * d \right) \right) * n$$

$$footprint = (a + x) * (b + x) * n$$

$$n = \frac{d * m}{h_{max}}$$

$$m = \left(\frac{l}{\#_{seg}} \right) + 1$$

Formwork: props beams

Input

\square_{prop}	= d [m]
prop length	= l [m]
stacking height	= s [#]
i or b_2	
$\#_{\text{props}}$	= m [#]
$\text{length}_{\text{beam}}$	= l [m]
spacing _{cross beams}	= k [m]
forming sections	= $\#_{\text{sec}}$ [#]
pathspace	= x [m]

Quantity – Space conversion

$$V = \left(\frac{D * (i - (s - 1)) + D * i}{2} + x \right) * D + (s - 1) * \sqrt{D^2 - \left(\frac{1}{2}D\right)^2} * (l + x)$$

Footprint = $(D * i + x) * (l + x)$

$m = i * s - ((i - (s - i))) * s$

$$m = \left(\left(\frac{l}{\frac{\#}{\text{seg}}} + 1 \right) * 2 \right)$$