Quantitative Models to Enhance The Flow of People and Goods at Hospital Dr. Nélio Mendonça

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Abstract: During the last decades there have been significant changes in demographic patterns. The world's population has increased due to high birth rates observed in developing countries. However, the Portuguese reality and many other developed countries, is a low birth rate and a high aging population, caused mainly by technological developments. This leads to higher demand for healthcare, a more frequent demand and that suggests complex and prolonged care. Today, hospitals face resource coordination challenges when trying to satisfy the increasing demand, in facilities that were built to process fewer people. Meaning that the logistics operations in hospitals are significantly affected. This situation has an impact in Hospital Dr. Nélio Mendonça (HNM) personnel, that in a constant basis resource to elevators to move around the building. There are big flows, and uncoordinated, to the elevators, causing high waiting times and some users insatisfaction. Hence, the present paper deals with a scheduling problem regarding elevator use, in hospital environment. In order to try to reduce the waiting times, that are being felt in HNM, operational information is gathered, and an Integer linear programming model is built. The development is done in GAMS and solved by CPLEX algorithm. The main activity performed by the mathematical formulation is to allocate users, to elevators, in a way that waiting times can be minimized. As a result, different kind of physical impact scenarios allow, some users, to have solutions that can be translated to daily waiting times that can vary between 676 seconds to none.

Keywords: Hospital Logistics, Integer Linear Programming, Distribution Scheduling, Elevators; Patients and Goods flow

1. Introduction

The scope of this paper is related with a scheduling problem regarding elevator use. The designed approach aims to reach a waiting time reduction for an elevator that can fulfill its user's needs. Hence, by respecting all users, the objective is to find a better coordination and efficiency in the elevator use process. The development of the study is executed at Hospital Dr. Nélio Mendonça (HNM), a central Hospital, located In the Portuguese island, Madeira. Therefore, must be capable to match their supply with all the population demand for healthcare.

Nowadays, and since past decades, the world's population is facing an increase. However, more evident, and felt, in developing countries, since is possible to find regions, and countries, where the average population age is increasing (Taagepera, 2014). Consequently, Hospitals may face a time where there is the need for more attention regarding healthcare seekers, that are becoming more frequent and that require longer stays (Howdon & Rice, 2018). Thus, strongly impacting the complexity of, already built, hospital logistics flows. Mainly due to the proportionality between aging and healthcare demand (Wittenberg *et al*, 2017).

HNM is surrounded by this environment. It needs to satisfy a higher universe of patients, that are becoming elderly. A higher number of patients means bigger needs for pharmacy, clinical material, food, hospital linen, and ends up producing more waste. This way, a group of hospital distribution workers identified the presence of high waiting times for elevator use. Creating the motivation for an overview over the elevator use process that occurs at HNM.

As a response, an integer linear programming model is built, and used to help the allocation of users to elevators, in different scenarios, to time slots that suits them best. Having, always, consideration for the potential waiting time expected. The model is feed by data gathered in HNM, where we identify usage patterns and operational constraints as inputs.

2. Literature Review

The flow of people inside buildings is a demanding activity. The degree of difficulty, of flow operations, are linked with factors as the mode and the type of movement, as well as its complexity (Barney & Lutfi Al-Sharif, 2015). Before the edification of a building, that will deal with a flow of people and goods, a set of requirements must be achieved. A detailed analysis can allow a correct structure dimension that might be able to deal with different, and simultaneous, routes. This detailed attention for structure dimension can be found, in an initial phase, by Tregenza (1971,1976). With respectively, a study about the prediction of passenger lift performance in multi-story buildings and, an overview about the design of interior circulation. Also, Kavouna (1993) dedicated some research to the topic, by offering a work regarding pedestrian traffic calculations among linearly connected vertical modes. More recently, other academics show works related with elevator use (Sorsa et al, 2016; Chen et al, 2016; Al-Sharif, 2017). Mainly, by addressing approaches to find solutions that can prevent, and help, to deal with extreme flow situations. Although some works are inserted in a design context, meaning that the possibility of dimensioning is present, others don't. Hence, the approach must be done through a demand shaping to a more suitable configuration use (Al-Sharif, 2014). A capacity management, with already known constraints, that can prevent the occurrence of bottleneck situations.

An important milestone in this field, is the acknowledgement of the inefficiency of traditional empirical methods. As an outcome of that conclusion, approaches that take advantage of simulation and linear programming became common (Davies et al, 1995). However, isn't possible to identify an approach that is widely applied to deal, simultaneous, with the flow of people and goods. The flow within an institution, from the internal warehouse to the consumption point, isn't strongly present in literature (Volland et al, 2017). Regarding internal flow, meaning internal distribution, it's possible to see it identified with the concept of scheduling (Viergutz & Knust, 2014). It's an activity that is responsible for planning resources having in mind a group of to do tasks. The decision is related with activities sequence, to reach a given objective (Pinedo, 2002). The sequence of tasks can be responsible for a significant system improvement (Li & Ierapetritou (2008).

The context of the present paper is in a hospital environment, identified as the institutional building with the most complex network flows (Strackosch & Caporale, 2010). The flows that occurs in a hospital must be managed and coordinated. Melo (2012) classifies the hospital flows in two different categories, one dedicated to walking traffic, done mainly by professionals and visits. And other one, vehicle traffic, related with the flow of patients and all the logistic flow that allows a hospital to operate (Food, Linen, Procurement, Portable Devices, …). Strackosch & Caporale (2010) says that an effective boundary between these two categories is the ideal approach to manage hospital logistic flows.

As a response to the complexity, approaches that take advantage of quantitative models can be identified in the literature. With a strong presence of Operations Research (OR) methods, such as Simulation and Linear Programming. The application towards Healthcare increased by the development that the industry is facing (Gray, 2012). OR can offer a solid solution, by developing brand new approaches or by adapting methods and conclusion from similar situation with the one in analysis (Romero-Conrado *et al,* 2017). The management problems, in the healthcare context, that are possible to find in specialty journals (Health Care Management Science and European Journal of Operational Research), are, mainly, patients scheduling, resources scheduling and logistics in healthcare. Also, Brandeau (2016), share that OR application in Healthcare must be done along with the health professional, to diminish the potential Blackbox effect that can result from the interaction of two different fields of action. The attention to this detail can make a difference in the application, or not, of a OR study.

From the literature, is possible to identify an example within this context. Buzaglo (2011), presents a study that applies Mixed Integer Linear Programming to deal with a scheduling problem related with distribution activities that have their total processing time constrained by elevator availability. The modelling is done through GAMS and solve with CPLEX Algorithm, to find an optimal solution in an environment that deals with 12 elevators, and 145 services to fulfill weekly.

This paper tries to take advantage of the understanding gathered by previous works. And wants to understand, physically, the elevator usage system in HNM, and develop a support tool, with Integer Linear Programming, to help the allocation of users to elevators in given time slots.

3. Case Study

HNM is characterized by a group of buildings that, together, build the HNM complex. Within this complex, the building that is responsible for admissions is composed by 9 floors. From that number, 7 (1-8) are responsible to offer prolonged care in a diverse number of medical specialties. To deal with the fulfillment of the needs that health and logistics operations demand, the building is prepared with 7 elevators. Equipment that can be used by a group of 10 users. As seen, identified, in table 1 and 2.

Table 1 - Elevators present in HNM.

Elevators
PE 1 (People's Elevator 1)
PE 2 (People's Elevator 2)
LE 1 (Logistics Elevator 1)
LE 2 (Logistics Elevator 2)
SE (Scheduled Elevator)
ORE (Operations Room Elevator
FE (Food Elevator)

Table 2 - Users from HNM elevators.

Users	
Visits	Sterilization Distribution Workers
Professionals	Food Distribution Workers
Linen Distribution Workers	Waste Collection Workers
Patients	Surgical Patients
Pharmacy Distribution Workers	Provisioning Distribution Workers

Each group of users have different characteristics that can be reflected in the elevator usage pattern. This way, aided by a physical presence in the center of the operation, it's possible to identify the following kind of information:

1. Users that have scheduling restriction in elevator use (Their operations need to occur in certain timetables and in a given Elevator);
2. Users that have, simultaneous or even intercalated, restriction regarding elevator sharing with other users;
3. Users that have flexibility in their operations that resource to elevators;
4. Duration of the tasks, of each user, that uses elevators;

The identification of the previous characteristics is only possible by a direct contact with the operation and with the people in HNM. That information allows to reduce the scope of the work, since restrictions that impact the possible approaches are discovered.

Having in mind the information gathered in the field, is possible, in a justified way, to simplify the number of users and elevators to work with. Regarding the elevators, the number of elevators that need to be considered are 4 (PE, LE, SE, FE). Elevators PE and LE share the same calling button. The elevator that is near the calling floor is allocated to the call. This way, it's possible to simplify and transform two elevators in only one. Elevator ORE, is dedicated to surgical patients, hence there is the need to guarantee a sterile environment. Turning impossible to share the elevator with other users.

In the other way, the users to be considered, and to become part of the solution, are only 6 (Linen Distribution Workers, Pharmacy Distribution Workers, Sterilization Distribution Workers, Food Distribution Workers, Waste Collection

Workers and Provisioning Distribution Workers). The reduction is related with restriction that were found during the case study analysis of HNM operation.

Professionals and Patients represent a group of users that are always present in the system, being impossible to assign themselves to timeslots, since they would occupy all the available ones. Users like surgical patients, since they can only be allocated to one elevator, and carry impossibilities of elevator sharing, there is no need to be incorporated in the approach. Regarding the user Visits, they are inserted in a very constrained environment in HNM, motivating, for them, dissatisfaction about waiting times. Due to restriction imposed by HNM, based on sanitation reasons, is not possible for them to use another elevator. Also, the timetable where the visits occur, is hard to change since they are linked with normal lunch break and after work hours. This way is not possible to schedule their use. Turning possible the decision of removing them from the users to be considered.

This way is possible to reduce HNM operation, for modelling purposes, to a group of users (6) that can use a certain group of elevators (4) to do tasks related with hospital environment. These tasks include visits to the different floors, with the objective to conduct operations with a certain duration. After the operation finishes, the user returns to the starting point. If the work is done in cycles, then the same procedure repeats.

4. Methodology

A mathematical model is developed to perform a simple task. To allocate users to elevators, where their tasks can take place, respecting possible timetable restriction that may occur. Although some operational constraints removed users and elevators from the approach. Other constraints need to be incorporated in the modelling process. Such as, timetables to respect by mandatory users and attributions between elevators and users. Also, to guarantee an outcome that delivers timeslots needed for the users, as the same time that blocks others that are mandatory for a different group of users. Always having in consideration, the possible waiting time outcome that a given timeslot offers.

The following information presents the generic mathematical formulation that worked as a basis to develop the present approach to offer insights regarding elevator use dynamics in HNM.

Index

u – Users
e – Elevators
t – Time slots
i – Set Identification/Numeration

Sets

$U = \{1,2,\dots,u,\dots,NU\}$, *Set off all users*
$E = \{1,2,\dots,e,\dots,NE\}$, *Set of all elevators*
$T = \{1,2,\dots,t,\dots,NT\}$, *Set of all time slots*
$I = \{1,2,\dots,i,\dots,NI\}$, *Set of all identification/numeration*

Subsets

$UC_i = \{1,2,\dots,u,\dots,NUC\}$, *Set with users that are restrict to a given set of elevators. There can be many subsets as many different relations users-elevators there is.*

$EC_i = \{1,2,\ldots,e,..,NEC\}$, *Set with elevators that are restrict to a given set of users. There can be many subsets as many different relations users-elevators there is.*

$UO_i = \{1,2,\ldots,u,..,NUO\}$ *Set of users that have mandatory timetables to respect. There can be many subsets as many users have different mandatory timetables to respect.*

$EO_i = \{1,2,\ldots,e,..EO\}$, *Set of elevators that are used by users that have mandatory timetables to respect. There can be many subsets as many elevators have different users that have timetables to respect.*

$TO_i = \{1,\ldots,t,\ldots,NT0\}$ *Set with timeslots that need to be performed by a given set of users. There can be many subsets as many timetables there is to be respected by different users.*

$UF_i = \{1,2\ldots,u,\ldots,NUS\}$ *Set with users that have timetable flexibility in a given set of elevators. There can be many subsets as many users have different timetable flexibility.*

$EF_i = \{1,2\ldots,e,\ldots,NES\}$ *Set with elevators that are used by a set of users that have timetable flexibility. There can be many subsets as many elevators are used by users with different flexible timetables.*

$TFi = \{1,\ldots,t,\ldots,NTF\}$ *Set with timeslots that range the working hour of users that have timetable flexibility. There can many subsets as many different working hours ranges are used by users that have timetable flexibility.*

Parameters

$Tesp_{e,t}$ *Average waiting time felt in elevator e, in the time slot t (Seconds)*

$Slotsobrigatorios_u$ *Number of slots that user u is required to fulfill*

$Slotsnecessarios_u$ *Number of slots that user u needs for their operation, in daily terms.*

Decision Variables

$y_{u,e,t}$ *- Binary Variable that takes value 1 if user u makes a trip in elevator e, on time slot t.*

Objective Function

$$Min\ Z = \sum_{t\in T}\sum_{e\in E}\sum_{u\in U} y_{u,e,t} \times Tesp_{e,t} \qquad (1)$$

Constraints

$$\sum_{u\in U} y_{u,e,y} \leq 1 \qquad \forall\, e\in E\,, t\in T \qquad (2)$$

$$\sum_{u\in UC_i}\sum_{t\in T} y_{u,e,t} \geq 1 \qquad \forall\, e\in EC_i\,, \quad i\in I \qquad (3)$$

$$\sum_{u\in UC_{i+1}}\sum_{t\in T} y_{u,e,t} = 0 \qquad \forall\, e\in EC_i\,, \quad i\in I \qquad (3.1)$$

$$\sum_{t \in TO_i} \sum_{e \in EO_i} y_{u,e,t} = Slotsobrigatorios_u \qquad \forall\, u \in UO_i \,, \quad i \in I \tag{4}$$

$$\sum_{t \in TO_i} \sum_{e \in EO_i} y_{u,e,t=} \; Slotsnecessarios_u \qquad \forall\, u \in UF_i \,, \;\; i \in I \tag{5}$$

$$y_{u,e,t} \in \{0,1\} \quad \forall\, u \in U \,, e \in E \,, t \in T \tag{6}$$

Objective function (1) models the total time waiting for all the users. Constraints (2) guarantee that only one user is allocated, in the same timeslot, to a given elevator. This way, spreading the elevator use across the different timeslots available. However, these constraints can be responsible to create an infeasible solution in case of higher timeslot demand, than the one available to use. Constraints (3) and (3.1) work together to guarantee that the assignment user-elevator is respected during the allocation. Showing the possible combination (3) and excluding combinations that aren't possible (3.1). Constraints (4) guarantee that a set of slots are occupied by users that have hard restriction related with timetable. Constraints (5) offer possible range of timeslots to users that have flexibility of allocation. Constraints (6) model the variables domain.

5. Case Study Solving

HNM elevator dynamics is identified as very complex. The presence of constraints that diminish the solution space offer a block to any approach. Turning only possible to offer flexibility to some users, having others with very strict schedules to fulfill, to respect coordination among different entities that are external to the hospital.

The existence of this degree of complexity creates the need to work with scenarios that can be translated by physical changes in the HNM. Changes that can have an impact in the elevator use operation. Becoming possible to reduce, one by one, the identified constraints. This way, a set of six scenarios are built and analyzed. Presented in the following table, numerated as 3. Table 4, represents the inputs that feed the mathematical formulation to offer the solution for the scenario 1, general case.

After all the data collection related with HNM operation, it becomes clear that not all users can be subject to changes. This way, the user Pharmacy and Provisioning, are the ones that have flexibility to become allocated within their working hours. It's a couple of users that have, currently, scheduling problems that makes them live high waiting times. Other users have strong impossibilities that don't allow them to have their operation occurring in a different schedule.

As an answer to those impossibilities, the scenarios try to create hypothetic scenarios where physical changes allow users to act differently. As already presented in table 3. The results of those scenarios can be found in table 5, where the amount of new free space is showed, as well as, the result given by the objective function. It represents the waiting time that the users Pharmacy and Provisioning are expected to suffer, on a daily operation.

Table 3 - Scenarios to apply the mathematical formulation, as well as their assumptions.

Scenarios	Assumptions
1 – General Case	Respect for all HNM restrictions; Respect for the possible attribution user-elevator; Respect for the scheduled considered mandatory;
2 – Installation of a tube dedicated for waste	Free slots allocated for user Waste → Remove user Waste Allocate new users, compatibles with the elevator
3 – Installation of a tube dedicated for dirty linen	Free slots allocated to the task of collecting dirty linen → Remove the slots dedicated for that operation Allocate new users, compatibles with the elevator
4 – Ampliation of the storage space reserved for clean and dirty linen	Less frequency in the delivery and picking of linen; Free some slots allocated to the user Linen → Dimensioning the need of slots Allocate new users, compatibles with the elevator
5 – Ampliation of the food elevator box	Bigger elevator means faster operation time on lunch and dinner distribution and picking operation → Dimensioning the need of slots Allocate new users, compatibles with the elevator
6 – Scenarios 2 and 4 together	Union between the assumptions from scenarios 2 and 4

The modelling dynamics tries to find suitable places, where the waiting time is reduced. The time horizon is between 07:00 to 19:30, and divided in similar parcels of 30 minutes. A number that can be seen as fair for an operation, having in mind the time that users spend in the system. In this context, the elevators FE and SE are identified as having waiting time zero. Since they work on a key basis and are already scheduled between some users. The other elevators LE and PE, they work in a sharing basis, with different users. However, patients when move, with the help of professionals, have always priority in the system, helping to create longer waiting times. This way, for simplification purposes, the waiting time collected is based, mainly, In the type of use that is given by those users. However, if free waiting time slots are available, they turn the two elevators very appealing for the model to choose. When in the absence of spaces offered by those elevators, the model resource to shared elevators that carry waiting times. In this context, the scenarios try to find a solution to free up space from the elevators identified as appealing. Therefore, the solution that is pursued offers a scheduled utilization that tries to allocate users that are in elevator EL, to elevators FE and SE.

The solution offered by scenario 1 can be seen in figure 1. The other scenarios offer similar solution to that one, replacing red squares, that are being free, to green ones. This way decreasing the number of used slots in elevator LE, hence, also, decreasing the expected waiting time. These solutions try to offer a better coordination between the different users and elevators. By having a shared knowledge of how the different flows interact. Offering positive solution for some users, while leave other elevators without a big amount of interruptions.

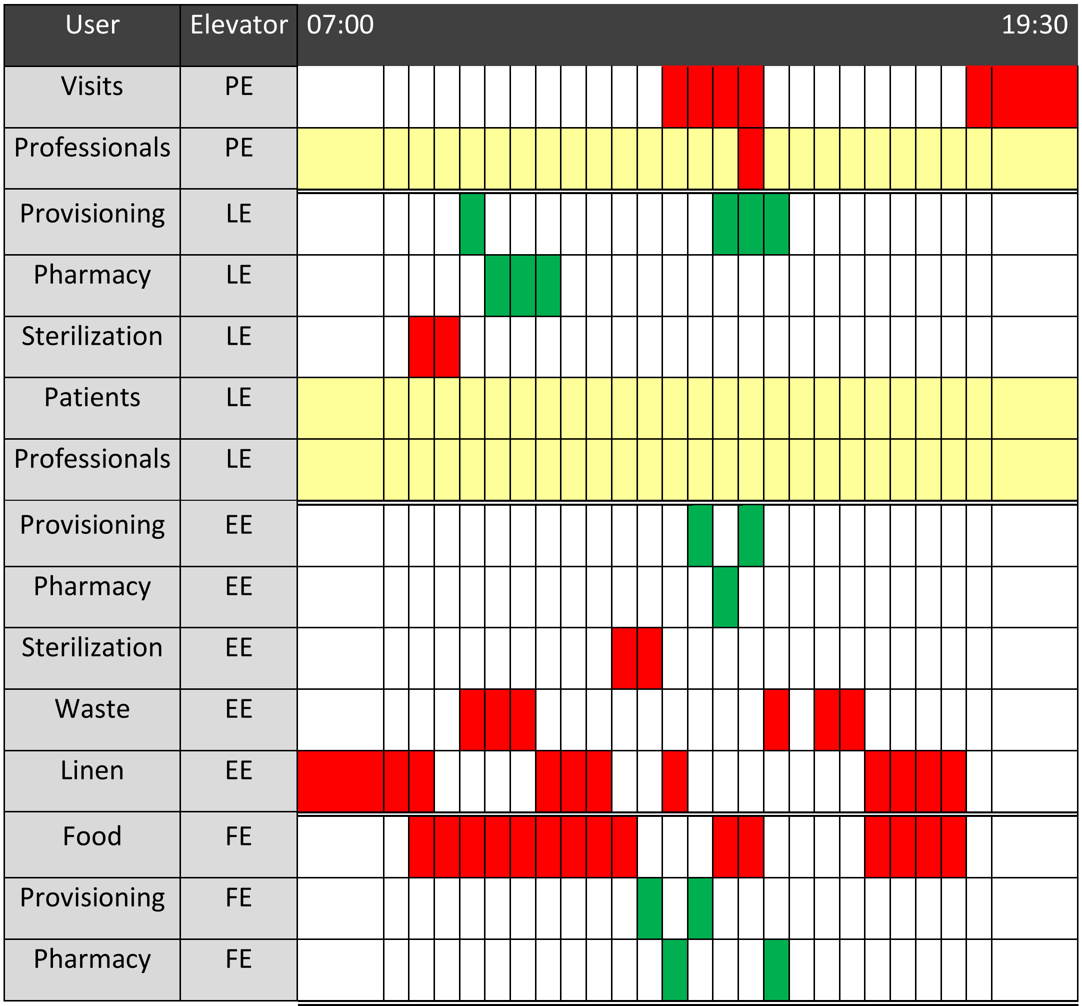
Table 4 - Data inputs for the model, related with scenario 1

Elevator	User	Schedule	Slots
PE	Visits	13:00 – 15:00 || 19:00 – 20:00	6
	Professionals	Always Present	-
LE	Pharmacy	Free (09:00 – 16:00)	6
	Provisioning	Free (09:00 – 16:00)	8
	Patients	Always Present	-
	Sterilization	08:00 – 10:00	2
	Professionals	Always Present	-
EE	Waste	09:00 - 10:30 || 15:00 – 15:30 || 16:00 – 17:00	6
	Linen	07:00 – 08:30 || 10:30 – 12:00 || 13:00- 13:30 || 17:00 – 19:00	11
	Sterilization	12:00 – 13:00	2
	Pharmacy	Free (09:00 – 16:00)	
	Provisioning	Free (09:00 – 16:00)	
FE	Food	08:00 – 12:30 || 14:00 – 15:00 || 17:00 – 19:00	15
	Pharmacy	Free (09:00 – 16:00)	6
	Provisioning	Free (09:00 – 16:00)	8

Table 5- Objective function results, by scenario and with the amount of new free slots.

Scenarios	New Free Slots	Waiting Time (Seconds)
1 – General Case	-	676
2 – Installation of a tube dedicated for waste	6 (3 Hours)	237
3 – Installation of a tube dedicated for dirty linen	7 (3,5 Hours)	338
4 – Ampliation of the storage space reserved for clean and dirty linen	4 (2 Hours)	237
5 – Ampliation of the food elevator elevator box	4 (2 Hours)	440
6 – Scenarios 2 and 4 together	10 (5 Hours)	0

Figure 1 - Solution from scenario 1. Red means mandatory use, Green represents the occurred allocation and yellow shows users that are always present in the system.



6. Conclusions

The current paper offers a solution for the use of the elevators in HNM. The usage process is identified as very complex, limiting the kind of approaches that can be taken, due to high constraints. Mainly, safety, hygiene and convenience constraints imposed by HNM administration. The first scenario offers the solution asked by HNM administration, however, the other scenarios try to offer solutions that can impact the complexity of the HNM network flows. By finding physical solutions that can alter the constrained state of different users. This way, offering solutions that can vary between 676 to none seconds of waiting time.

An integer linear programming model is proposed to allocate slots to several users. This approach offers insights for the elevator use operation in HNM. Is confirmed, as expected, that the flow of people in shared elevators is more intense between the 12:00 to 16:30. Being related with the patient's routine in the HNM. This way, turning possible to suggest, as the model output checks, that the most flexible users should reorganize their distribution operations to avoid critical schedules. About the already scheduled elevators, utilization gaps are found. Those gaps can offer a solution, to some suitable users, if the use occurs with respect for hygiene aspects. Therefore, offering a solution that allows to spread utilization and harmonize using percentage across all the elevators. Taking advantage of elevators with absolutely zero waiting time, may suggest that the distribution activities can be organized to take the most of this elevator. Meaning, for instance, to realize all the distribution and to, only after, realize all the unpacking.

However, it is possible to recognize limitations from the model. The waiting times considered are based on data gathered from an already done allocation, although the majority of waiting time is related with the use done by patients and professionals (in elevator LE). Users that aren't, directly, contemplated in the modelling process. The solution provided in this paper would beneficiate from a simulation approach that is able to analyze, in a more efficient way, the HNM elevator operation. Since it represents a continuous analysis, with a temporal factor, that contrasts with this very same static approach, developed in this paper. A simulation approach, with representative data from the system, would offer an opportunity to look at the different scenarios with a set of KPI that could offer precious insights about the solution in analysis. Linked with this paper, the simulation could criticize the solutions and the results obtained. By a full replication of the system interaction.

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