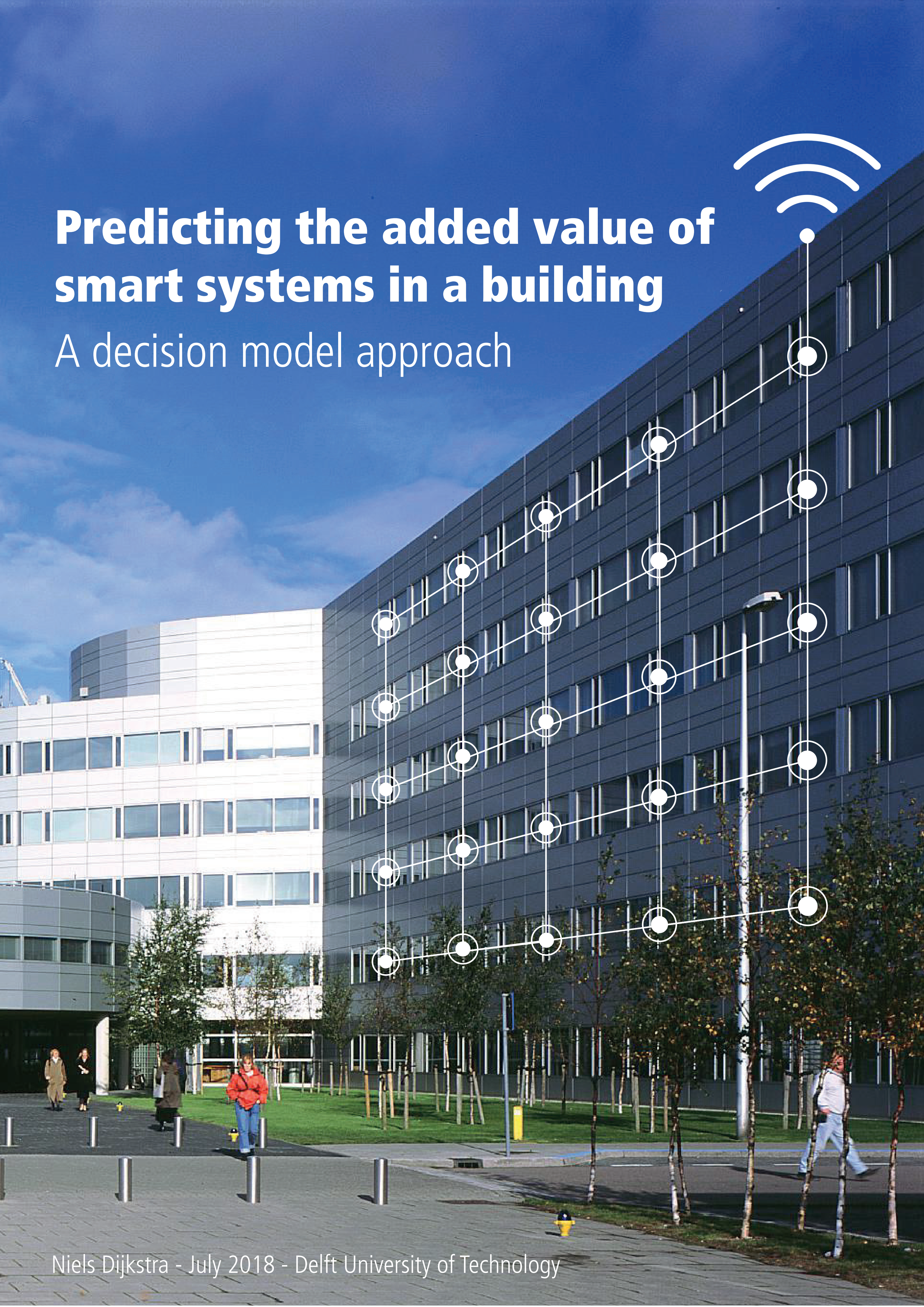
Predicting the added value of smart systems in a building

A decision model approach



Niels Dijkstra - July 2018 - Delft University of Technology

Colophon

Predicting the added value of smart buildings in a building

Delft University of Technology
Faculty of Architecture and the Built Environment
Master Management in the Built Environment
Graduation subject: Smart Real Estate Management

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Preface

Before you lies the conclusion of my master track 'Management in the Built Environment' at the Delft University of Technology. It is the final course to obtain the master diploma of the University.

The bachelor and master track that I have followed in the past six years has been a process of trial and error. As an architecture and real estate student I learned that the process of a good design is testing, evaluating, refining and improving. It is a process of working on a solution for days only to find out the approach is not suitable and a better option comes to sight, which means starting all over again. It is also a process of pioneering. For a student or professional in the field of architecture and the built environment it is not uncommon to find yourself in a unique situation, which asks for a customized solution. Creativity and innovation are the most important skills to have in such a situation. A quote by designer Alina Wheeler perfectly expresses my perspective on this process:

"Design is intelligence made visible" – Alina Wheeler

Design is a visible outcome of the process of testing, evaluating, refining and improving. You start with nothing and end up with an intelligent product.

This final report is a good expression of the quote. In the beginning I did not knew much about smart buildings, however a year later I graduated my master with this report about smart buildings. Smart buildings aims to improve many elements in the built environment and is an subject in which relatively little is known. This motivated me to choose this subject and gradually learn more about it.

Besides smart buildings the research also included decision-making theory and preference measurement as scientific theories. Together this has been an exciting learning curve. The report takes you through this learning curve and shows you how I came to from nothing and ended up with a final 'design'.

Enjoy reading!

Niels Dijkstra, July 2018

Summary

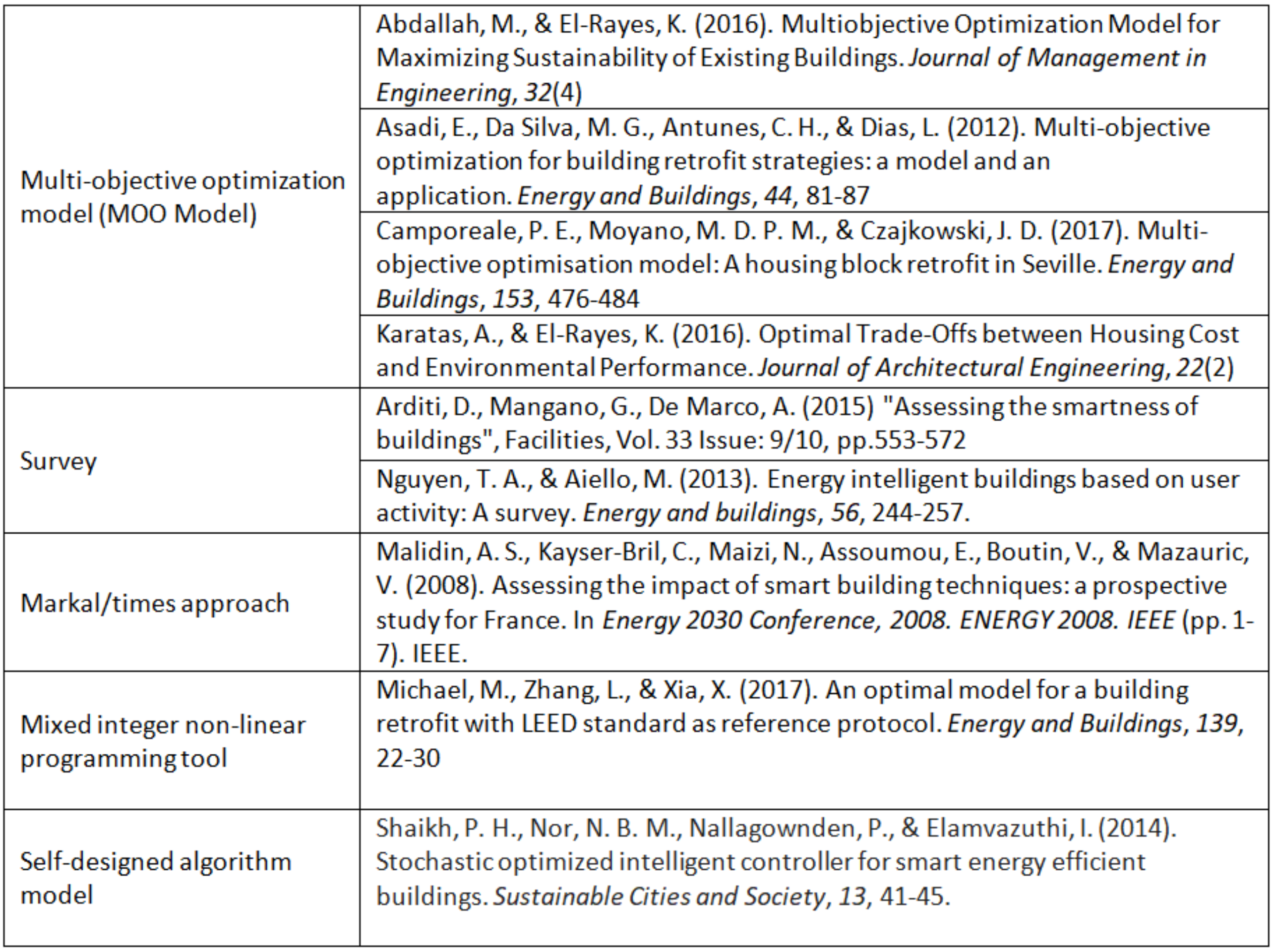
Smart systems have the potential to contribute to the objective of optimally attuning the building with changing demands, or in other words, to add value to the building. Real estate managers expressed their interest in smart systems to improve their supply.

One of the long-standing issues in the field of real estate management is the alignment of demand and supply. When building retrofit is initiated to comply with changing demands, the decision-maker has to deal with several criteria. This is called the multi-criteria problem and is characterized by the existence of multiple and competing criteria, a set of feasible and a set of constraints that should be taken into account to reach the best feasible solution (Asadi, 2012).

It is the field of decision theory, that is concerned with the multi-criteria problem and the process of identifying the best feasible solution (Binnekamp, 2010). This thesis aims to present a mathematical model that supports the decision-maker in the selection of a smart system.

Research problem

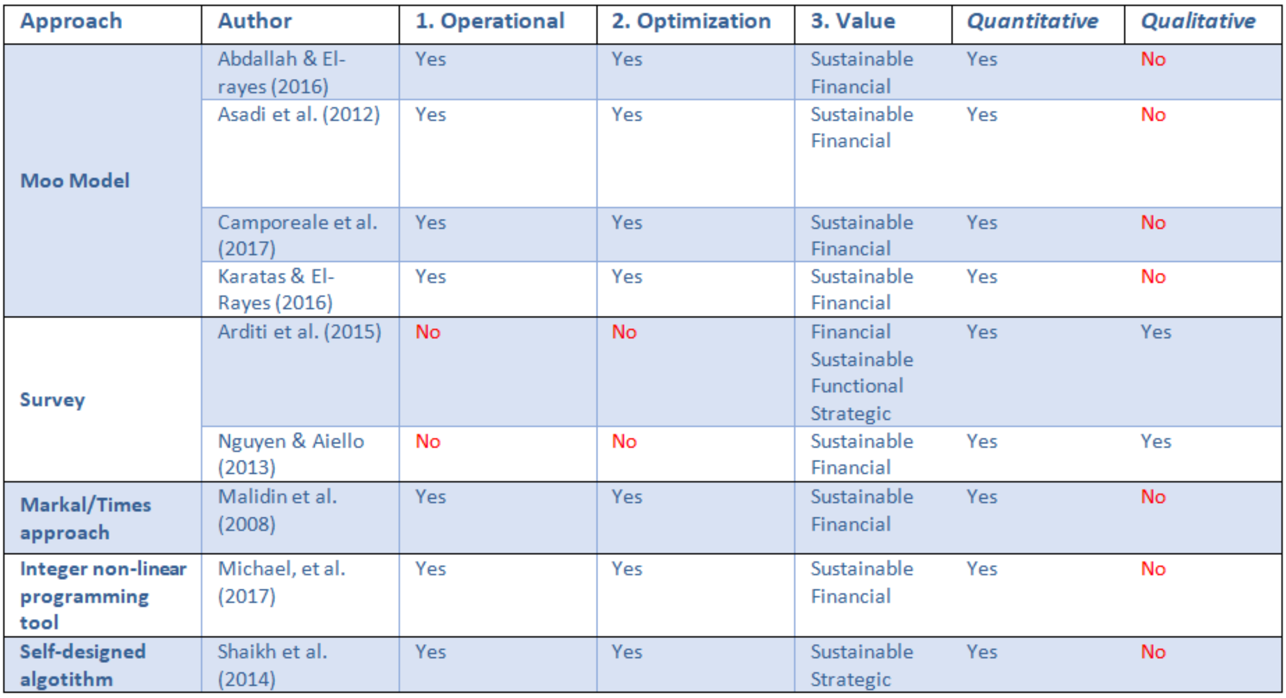
When the decision-maker cannot decide based on their own judgement and experience they need to have a tool to aid them in this process (Anderson, 2016). A literature search has been done to find relevant research papers that provide a tool to aid a decision-maker in the process of deciding which smart system to choose. Nine papers came forward out of the literature search (see figure 1).



Multi-objective optimization model (MOO Model)	Abdallah, M., & El-Rayes, K. (2016). Multiobjective Optimization Model for Maximizing Sustainability of Existing Buildings. *Journal of Management in Engineering*, *32*(4)
	Asadi, E., Da Silva, M. G., Antunes, C. H., & Dias, L. (2012). Multi-objective optimization for building retrofit strategies: a model and an application. *Energy and Buildings*, *44*, 81-87
	Camporeale, P. E., Moyano, M. D. P. M., & Czajkowski, J. D. (2017). Multi-objective optimisation model: A housing block retrofit in Seville. *Energy and Buildings*, *153*, 476-484
	Karatas, A., & El-Rayes, K. (2016). Optimal Trade-Offs between Housing Cost and Environmental Performance. *Journal of Architectural Engineering*, *22*(2)
Survey	Arditi, D., Mangano, G., De Marco, A. (2015) "Assessing the smartness of buildings", Facilities, Vol. 33 Issue: 9/10, pp.553-572
	Nguyen, T. A., & Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. *Energy and buildings*, *56*, 244-257.
Markal/times approach	Malidin, A. S., Kayser-Bril, C., Maizi, N., Assoumou, E., Boutin, V., & Mazauric, V. (2008). Assessing the impact of smart building techniques: a prospective study for France. In *Energy 2030 Conference, 2008. ENERGY 2008. IEEE* (pp. 1-7). IEEE.
Mixed integer non-linear programming tool	Michael, M., Zhang, L., & Xia, X. (2017). An optimal model for a building retrofit with LEED standard as reference protocol. *Energy and Buildings*, *139*, 22-30
Self-designed algorithm model	Shaikh, P. H., Nor, N. B. M., Nallagownden, P., & Elamvazuthi, I. (2014). Stochastic optimized intelligent controller for smart energy efficient buildings. *Sustainable Cities and Society*, *13*, 41-45.

Figure 1. previous research focussed on the multi-criteria problem related to smart buildings

The nine papers consist of five different approaches. All five approaches are analysed based on the following three constraints. The approach should be operational. This means that it should be future-oriented and focus on improving a situation, in this case by implementing an upgrade measure, such as a smart system, in a building. Secondly, the research model should be able to find or design the optimum or best alternative. Third, the model should be able to make a trade-off between conflicting quantitative and qualitative values.



Approach	Author	1. Operational	2. Optimization	3. Value	*Quantitative*	*Qualitative*
Moo Model	Abdallah & El-rayes (2016)	Yes	Yes	Sustainable Financial	Yes	No
	Asadi et al. (2012)	Yes	Yes	Sustainable Financial	Yes	No
	Camporeale et al. (2017)	Yes	Yes	Sustainable Financial	Yes	No
	Karatas & El-Rayes (2016)	Yes	Yes	Sustainable Financial	Yes	No
Survey	Arditi et al. (2015)	No	No	Financial Sustainable Functional Strategic	Yes	Yes
	Nguyen & Aiello (2013)	No	No	Sustainable Financial	Yes	Yes
Markal/Times approach	Malidin et al. (2008)	Yes	Yes	Sustainable Financial	Yes	No
Integer non-linear programming tool	Michael, et al. (2017)	Yes	Yes	Sustainable Financial	Yes	No
Self-designed algotithm	Shaikh et al. (2014)	Yes	Yes	Sustainable Strategic	Yes	No

Figure 2. Analysis of previous research

Out of the analysis in figure 2, it could be concluded that there is sufficient research that aims to find an optimized solution to improve a building in a future situation. When doing so, conflicting values are taken into account such as minimum costs vs. maximum environmental performance or minimum energy use vs. maximum comfort. However, none of the operational models provide the possibility to include qualitative values. In the built environment, qualitative values are an important part of the added value of an intervention such as smart systems. Therefore, none of the existing models are sufficient in predicting the overall added value and a new approach is needed to be developed.

Research question

In order to develop an appropriate model to support the decision-maker in the multi-criteria problem the following research question and sub-questions needs to be answered:

How can a decision model predict the added value of a smart system?

The sub-questions are divided in the demand and supply which make up the situation of a multi-criteria problem:

1. Demand: Which parameters need to be present in the decision-model?

2. Supply: Which relevant design alternatives can be made based on existing smart technologies?

Smart building theory

The scope of the research is indoor positioning smart systems. Indoor positioning techniques determine the position of an object or a person (Mautz, 2012). The purpose of indoor positioning is to define the behaviour of the building and its users and support user activities in de building (Linder, 2017 and Kejriwal, 2016).

An indoor positioning smart system consists of four main elements: sensors, an integrated platform, internet-enabled devices and building facilities.

Sensors are placed throughout the building to collect data. The sensor nodes either communicate with a mobile device or sense a person. The sensor nodes that communicate with a mobile device commonly use Wi-Fi, Bluetooth Low Energy (BLE) or Visible Light Communication (VLC). The nodes that sense a person commonly use Infrared (IR), electromagnetic sensors or a camera. These are the two primary types of data collected in a smart building.

The sensors send their collected data to the integrated platform. The integrated platform is the main body of the grid where all the data is stored and saved. Structured and unstructured data from different internal and external sensors can then be aggregated here. The platform contains intelligent algorithms in order to translate the data into useful information. Secondly, machine learning methods based on evolutionary algorithms, genetic algorithms, neural networks, and other artificial intelligence techniques are necessary to achieve automated decision making (Gubbi, 2013).

The useful information is visualized in an application. Visualization is critical for an smart building as this allows interaction of the user with the smart system. With recent advances in touch screen technologies, internet-enabled devices such as smart phones and tablets have become the primary tool to access the visualized information (Gubbi, 2013).

The building consists of a variety of installations controlling things such as the indoor climate, facade, space, lighting, entry/exit points etc. The information from the integrated platform can be used to change and improve the operation of these installations. This can be done manually or automatically.

Smart building value

Smart technology aims at improving the building, or in other words, add value. The added value of a smart system can be defined in different ways. Arkesteijn et al. (2017: p.244) describes added value as following:

“We note that to decide is to choose. We choose the alternative that we prefer, and prefer the alternative that adds value. This means that value can be measured by measuring preference, that is, evaluating/judging the alternatives as to the value they add, and in this context, value and preference are equivalent”.

Based on the statement it is correct to use the preference of stakeholders to determine the added value of a smart system.

Research method

To measure the added value of a smart system, Preference Measurement is suitable, which is part of operational research. Within preference measurement there are two types: Preference Function Modelling (PFM) and Preference Based Design (PBD). PFM is an evaluation methodology, helping decision makers to choose the most preferred alternative from a set of predefined alternatives (Binnekamp, 2010). PBD is a design methodology, used to generate design alternatives based on preferences and weights. PBD is used when the design alternatives are not know beforehand (Binnekamp, 2010). Because the alternatives are known beforehand, PFM is chosen as the most suitable research method.

The PFM approach is based on the research of Arkesteijn et al. (2017) and includes the three types of rationality of decision-making: procedure, structure and substantive rationality. The procedure is a step-by-step plan elaborating on all elements that need to be achieved to come to the desired outcome. The structure consists of all the activities necessary to achieve one or multiple steps. Together they form a flowchart, which is the directory of the research (see figure 3). The substantive rationality is the mathematical decision model.

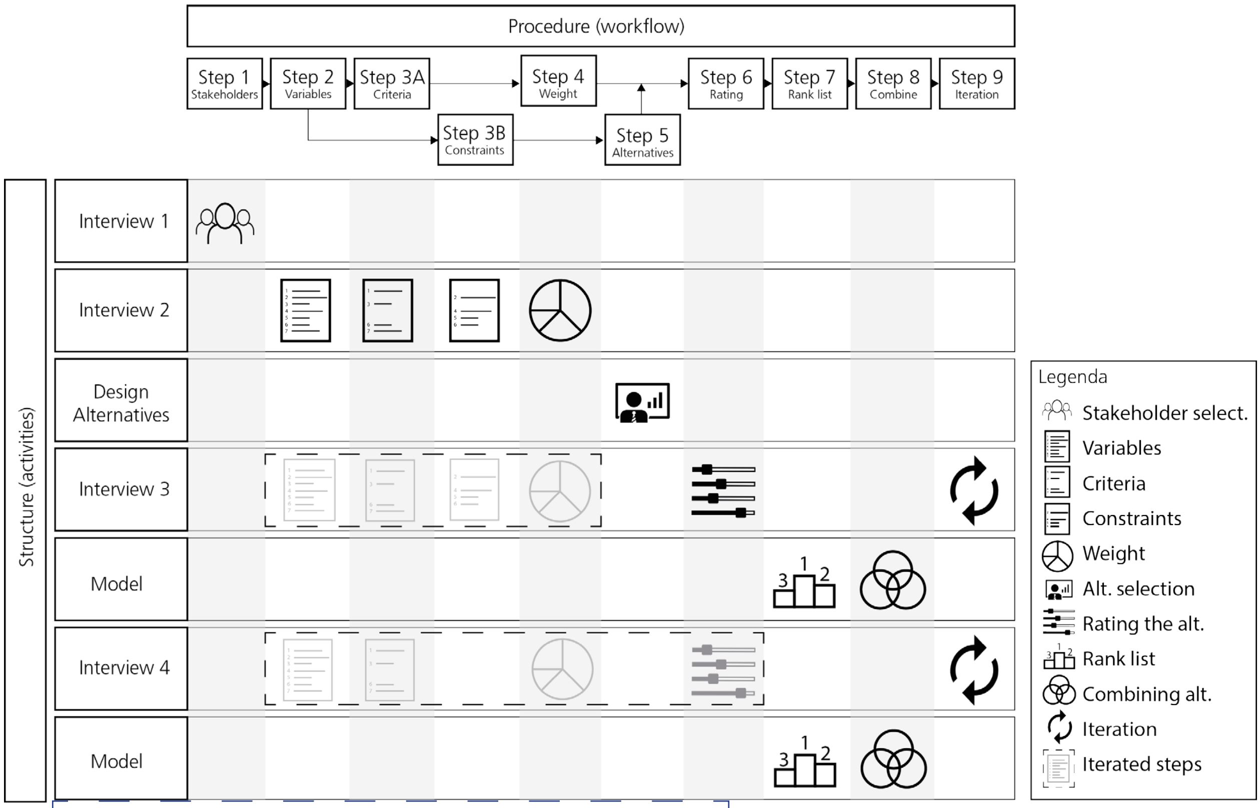


Figure 3. Flowchart (based on Arkesteijn et al., 2017)

Procedure:

1. Select stakeholders.
2. Stakeholders define variables.
3. Stakeholders Define constraints and criteria.
4. Stakeholder defines weight for each criterion
5. Define alternatives based on scope of the research and constraints.
6. Stakeholder rates each alternative per criterion.
7. Rank the overall preference score of each alternative.
8. Combine alternatives to create an optimum alternative.
9. Use iteration to improve the input given by the stakeholders.

In order to complete each of the steps, three activities are necessary: interviews, designing alternatives and modelling. In the interviews the input from the stakeholders is gathered, which consists of the variables (constrains and criteria), criterion weight and preference scores. The design of alternatives is necessary to establish a list of alternatives to be evaluated in the model. Modelling is necessary to calculate all input given and produce an output, which is a rank list of the overall preference score of each alternative (see figure 4).

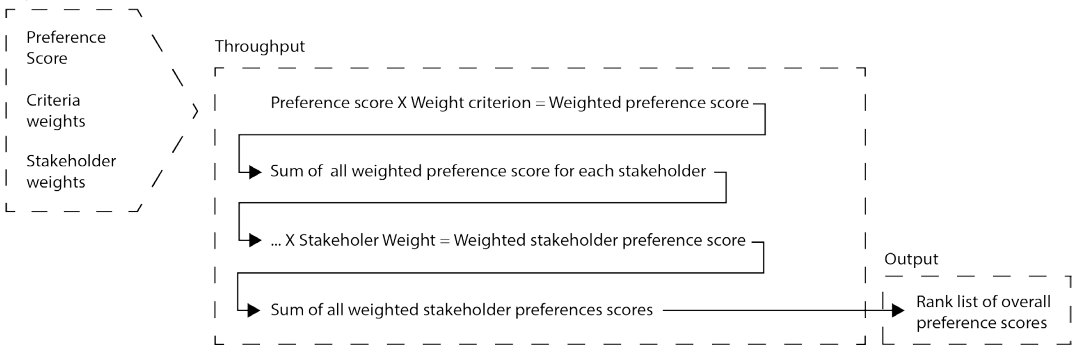


Figure 4.Principal structure of the model

The rating of alternatives is done in two ways: preference scaling and the Lagrange curve. For preference scaling the stakeholder is asked to score their least preferred alternative with 0, the most preferred alternative with 100 and the remaining alternatives in between. The score given to each alternative is the preference score and is done per criterion.

The Lagrange curve is used for criteria to which the alternatives tend to change. For example, the costs of an alternative could change over time. For the Lagrange curve the stakeholder is asked to define the value for which he would give a preference score of 0, 50 and 100. Based on these three points an preference curve can be created. On the curve the preference for each value can be found (see example figure 5).

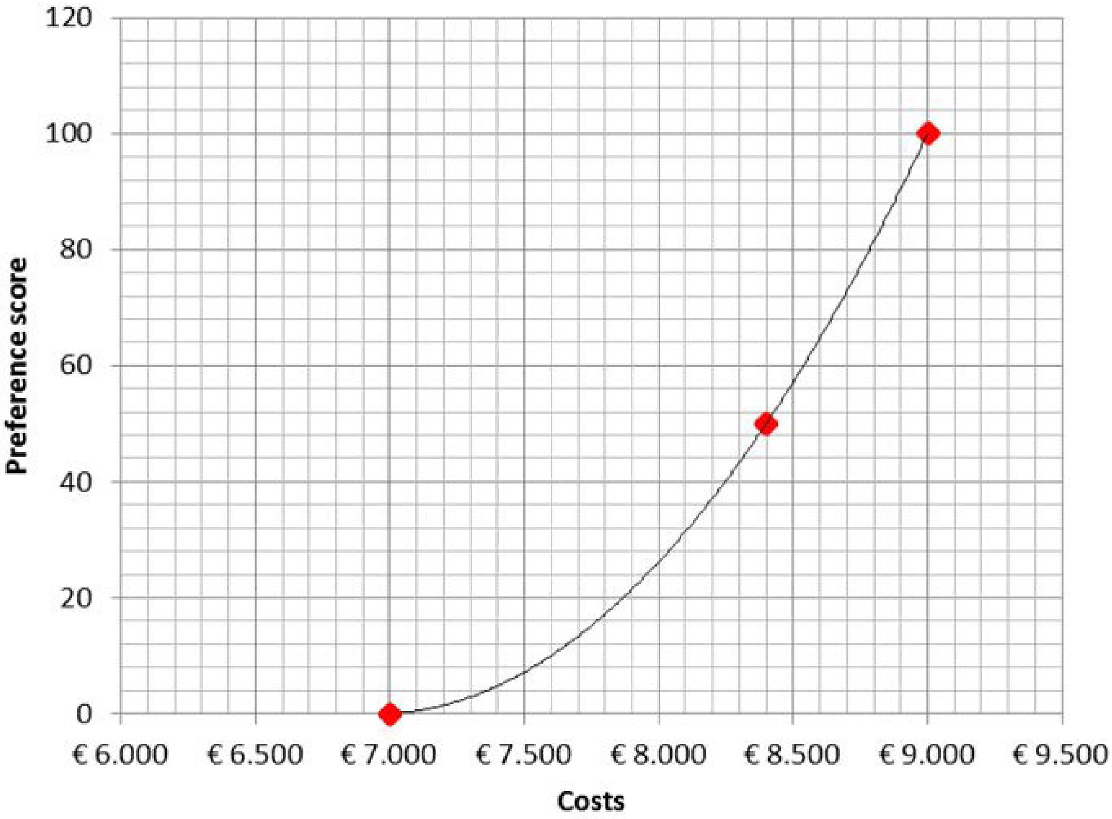


Figure 5.Lagrange curve

Research

For the research a single building of the portfolio of Schiphol Real Estate is selected: Schipholgebouw (SHG). The SHG is an office building which is selected to be transformed into a smart building. The research is explained using the procedure of the flowchart (see figure 6).

1. Select stakeholders

For the research seven stakeholders are selected: the property manager, investor, area developer sustainability advisor, technical property manager, tenant manager and users.

2. Define variables

At first the stakeholders defined 47 variables. Due to the process of iteration (see step 9) the stakeholders redefined the variables and determined 36 final variables, 17 of which are qualitative. The fact that a significant amount of the variables are qualitative indicates the importance of a model that's able to include qualitative values.

3. Define criteria and constraints

The research contains seven constraints; security, privacy, market maturity, scalability and integration with existing infrastructure and integration with the facility management system and Outlook. The variable 'market maturity' is defined as both a constraint and criterion. All other variables are defined as criteria.

4. Define weight

The stakeholders gave weight to their criteria by dividing 100% over their criteria. Secondly the decision-maker weighted the stakeholders. This process is done to define the importance of the criteria and stakeholders.

5. Select alternatives

The alternatives are the different solutions that are going to be evaluated. Based on the scope of the project a dialogue with twelve indoor positioning smart system suppliers was initiated. Out of the dialogue eight suppliers were selected that comply to the scope of the project and constraints defined by the stakeholders.

6. Rating of the alternatives

Before rating the alternatives, the stakeholders received all available information about each alternative in order to effectively rate them. All criteria were rated using preference scaling except for costs and tenant/user satisfaction. Because the values related to these criteria tended to change they were evaluated using the Lagrange curve.

7. Rank list

After all input parameters are given (preference score, criteria weight and stakeholder weight) the model is capable of calculating the overall preference score of each alternative. The highest overall preference score is the best decision, in other words, the alternative that adds most value. In this case the most preferred option is Cisco.

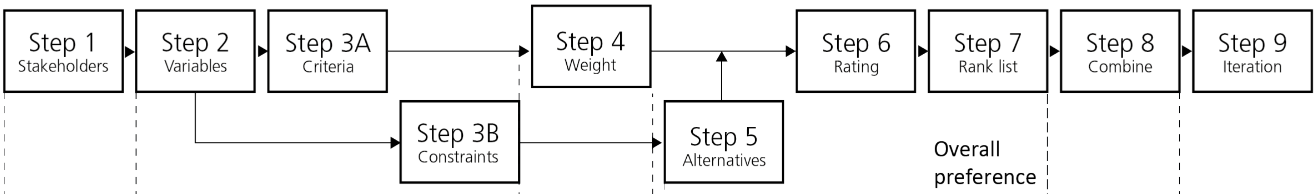
8. Combine

The model also formed a list of criteria including the alternative that scored best on each criterion. This list was a starting point for a discussing to further improve the most preferred option. Out of the discussion two key points came forward: to improve Cisco by including Infrared sensors and to revise the communication technology.

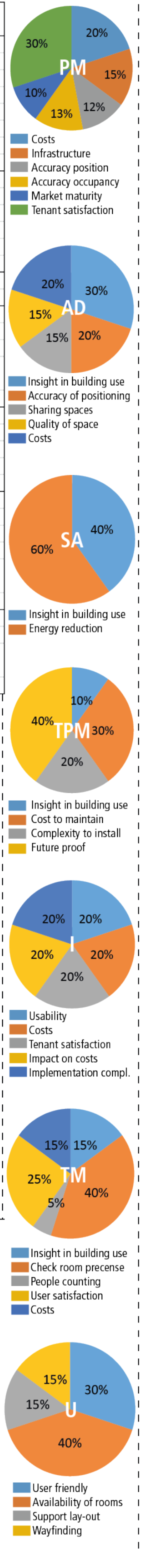
9. Iteration

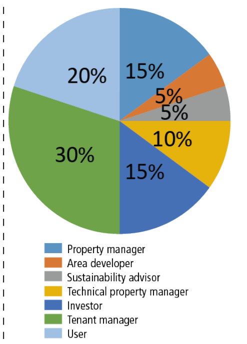
Iteration is used to improve the input given by the stakeholders. During the research process the stakeholders acquire new information which may lead to the need to change their input. The process of iteration allows the stakeholders to define their input as intended.

Procedure (workflow)



Side	Stakeholder	Variable	Constraint/ Criterion/ both
Owner	PM	Costs	Criterion
		Infrastructure	Criterion
		Accuracy position	Criterion
		Accuracy occupancy	Criterion
		Market maturity	Both
		Tenant satisfaction	Criterion
		Security	Constraint
		Privacy	Constraint
	AD	Insight in building use	Criterion
		Accuracy of positioning	Criterion
		Scalability	Constraint
		Sharing spaces	Criterion
		Quality of space	Criterion
		Costs	Criterion
	SA	Insight in building use	Criterion
		Energy reduction	Criterion
	TPM	Insight in the building use	Criterion
		Cost to maintain	Criterion
		Complexity to install	Criterion
		Integration with existing infrastructure	Constraint
		Future proof	Criterion
	I	Usability	Criterion
		Costs	Criterion
		Tenant satisfaction	Criterion
		Impact on costs	Criterion
		Implementation complexity	Criterion
Tenant	TM	Insight building use	Criterion
		Check precense in rooms	Criterion
		People counting in rooms	Criterion
		User satisfaction	Criterion
		Integration with FM system and outlook	Constraint
		Costs	Criterion
	U	User friendly	Criterion
		Availability of rooms	Criterion
		Support lay-out improvement	Criterion
		wayfinding	Criterion





	Overall preference score
CISCO	79,6
PHILIPS Lighting	71,1
octo	68,0
LONE ROOFTOP building intelligence	67,3
BLOO-LOC	60,1
bGrid®	52,1
iotspot	37,2
BLIP systems	30,7

Points of improvement:

- Communication method
- PIR sensing method

Point of future improvement:

- Camera sensing method
- Pedrsonalized sensing method
- Climate sensing method

Changing of variables:
all stakeholders changed their variables:
- 17 removed
- 10 added
- 3 changed
- 4 combined

Changing of weight
4/6 stakeholders changed weight
Note: due to changing variables

Changing of preference scores
2/6 stakeholders changed score

Figure 6. Summary of research procedure

Discussion

Out of the feedback given by the stakeholders one very important matter came forward. The existence of uncertainty in the model. The definition of uncertainty is the difference between the amount of information available and the amount of information required to take a decision (See figure 7, Winch, 2010). The stakeholders stated that the amount of information available was not sufficient and their input was subject to uncertainty. Especially the process of rating the alternatives was subject to uncertainty because of little knowledge about the smart system alternatives. This negatively influences the output of the model.

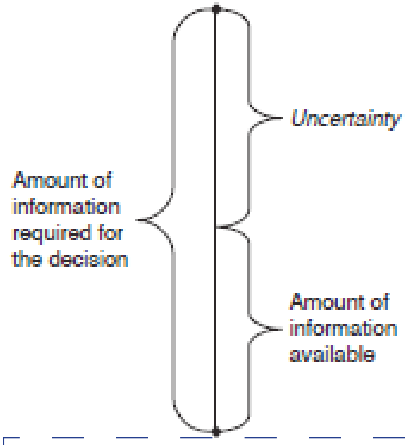


Figure 7.Uncertainty (Winch, 2010)

A quality of the research model is that it provides a custom-made outcome based on stakeholders input, which reflects a specific situation. The model is able to include all values that are of interest to the stakeholders and has no limitations regarding stakeholders and variables.

Alternative model

Because of the uncertainty problem, an alternative model is proposed which allows the expert to define alternatives, variables and preferences scores. This way the stakeholder is not involved in a process in which uncertainty is high. The stakeholder is only involved in the process of assigning weight to the criteria (see figure 8). The top part is done by the expert, is done once and results in a standardized model. The bottom part is done including the stakeholder and needs to be done for each decision-making problem.

The advantage of this model is that it is quick and easy to use. The disadvantage is that it limits the projection of reality. Because the criteria and scores are done by the expert, the subjectivity of the stakeholders is excluded. It is therefore also not possible to include qualitative values as they can only be scored by a stakeholder. For example, satisfaction.

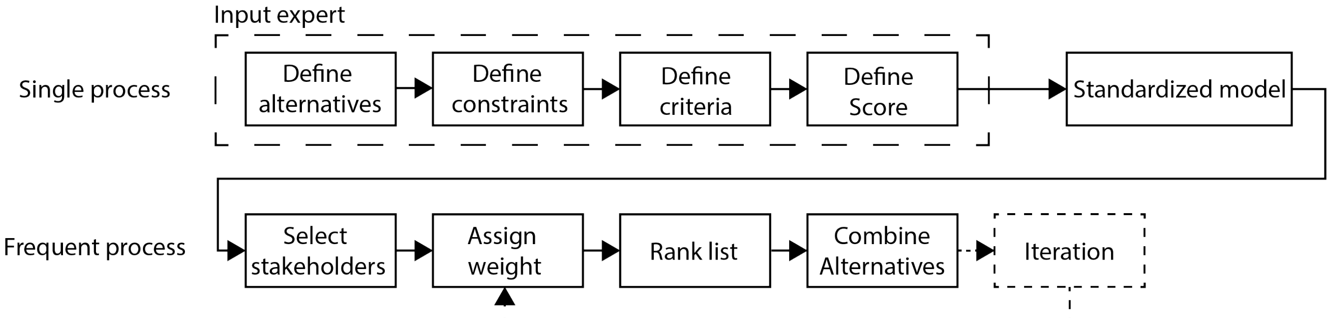


Figure 8.Alternative model

Conclusion

The conclusion gives an answer to the main research question and the two sub-questions, starting with the sub-questions.

Demand: Which parameters need to be present in the decision-model?

Preference Function Modelling is a method that enables one to apply mathematical analysis and calculations to quantitative and qualitative demands of multiple stakeholders. It allows stakeholders to determine their own input and translate it into mathematical parameters. The stakeholders define constraints, criteria, weight for each criterion and the preference score of each alternative on each criterion. The process results in three mathematical parameters: criteria weight, stakeholder weight and preference score.

Two techniques are used to define the preference scores: preference scales and the Lagrange curve.

Supply: Which relevant design alternatives can be made based on existing smart technologies?

The answer to this questions depends on the scope of the project. If the amount of alternatives is extensive, PBD (e.g. PAS approach) is more suitable and the supply will be designed in the course of the process. If the amount of alternatives is limited, the PFM (e.g. this research) is suitable and the supply will be selected beforehand. In the SHG case, the scope was indoor positioning, the amount of alternatives was limited and eight alternative were designed beforehand. The designs were made in collaboration with the market suppliers.

How can a decision model predict the added value of a smart system?

A preference-based decision model can predict the added value of a smart system by defining the preference score of each feasible alternative on each criterion and to calculate the overall preference score for each alternative. The overall preference score is the weighted sum of all preference scores. The overall preference score represents the value of a smart system and the highest score is predicted to add the most value.

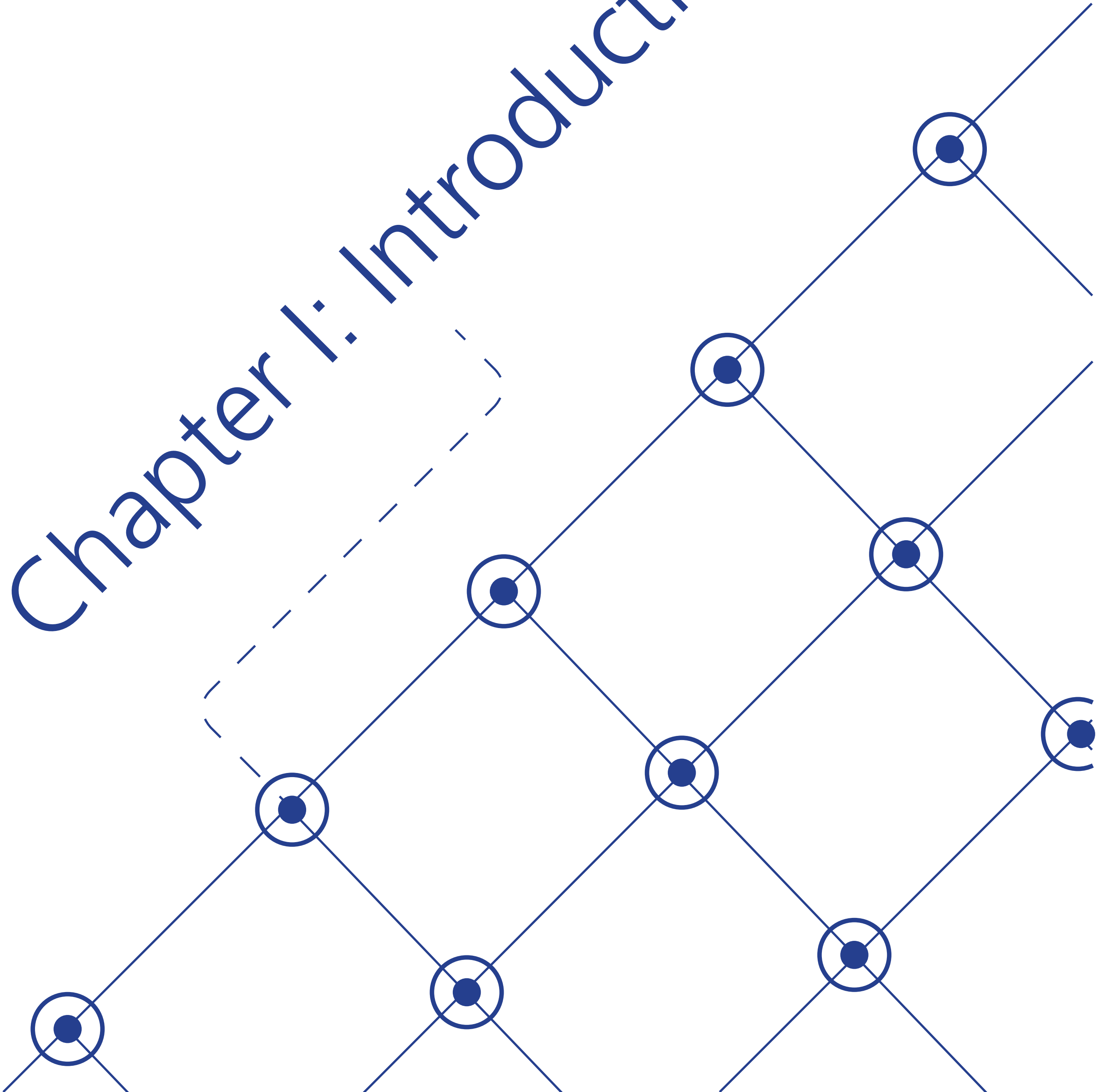
However, the prediction depends on the certainty of the input. High uncertainty will project a distorted prediction of reality. Uncertainty may have a number of factors but in this research a lack of knowledge appeared to be the main factor of uncertainty.

Glossary

API	Application Programming interface
BLE	Bluetooth Low Energy
BMS	Building Management System
CBD	Central Business District
CREM	Corporate Real Estate Management
IR	Infrared
PAS	Preference-based accommodation strategy
PBD	Preference Based Design
PFM	Preference Function Modeling
PIR	Presence infrared
PoE	Power over Ethernet
RSSI	Received Signal Strength Indicator
SHG	Schipholgebouw (Schiphol office building)
SRE	Schiphol Real Estate
VLC	Visual Light Communication

Table of content

Chapter I: Introduction



1.1 Introduction

The uprise of the internet changed the way we look at the built environment. The Internet of Things (IoT) is a suite of technologies and appli¬cations that equip devices and locations to generate all kinds of information (Kejriwal, 2016). The internet is used as a backbone to communicate data about condition, position or other attributes. A relatively new concept that is linked with the IoT is a smart building (Buckman, 2014). An academic view is given by Wang et al. (2012), agreeing that smart buildings are part of the next generation building industry, suggesting that they address both building issues and those of the user by utilising both computer and intelligent technologies to achieve an optimal combination. Smart technology also seems to provide a promising method for gathering a lot of data about building operation relevant to building management (Zhao, 2017). A smart system consists of several parts: sensors that capture the data, smart tools, which are internet-enabled devices, an integrated open cloud platform and the building installations. However, it's not the sensors, tools or installations that make a building smart, it's the ability to process and learn from all the data the sensors provide (Nouveau, 2017).

Smart buildings are part of the innovation of information and communication technology (ICT). In the field of Corporate Real Estate Management (CREM), the impact of these innovations in ICT is comparable to the impact of the first industrial revolution (de Jonge et al., 2009). The built environment changed dramatically due to these innovations. With the uprise of ICT, buildings are expected to meet increasingly higher and potentially more complex levels of performance (Arditi, 2015). CREM responds to these changes by adapting, improving and maintaining the value of real estate. Den Heijer (2011) defines this as the process between demand and supply with the overall goal to optimally attune the value of real estate.

In this thesis, the concepts of (adding) value and smart systems come together. Building owners, investors and developers (decision-makers) are often faced with the challenge of solving the mismatch between demand and their supply by implementing an optimal set of building upgrade measures (Abdallah et al., 2016). Smart systems offer the opportunity to use resources more efficiently, to support processes in the building and to create new revenue (Kejriwal, 2016). Smart systems have the potential to contribute to the process of optimally attuning building with the changing demands.

Taking advantage of this potential is a complex challenge. Asadi et al. (2012) states that when faced with the challenge of solving the mismatch between demand and supply, a multi-criteria decision problem is commonly encountered. This is characterized by the existence of multiple and competing criteria; a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and a set of constraints that should be taken into account to reach the best feasible solution. Due to the large number of criteria, it is not straightforward for a user to identify the optimal system for a particular application (Mainz, 2012). It is the field of decision theory, which is concerned with the problems of identifying the best choice to take (Binnekamp, 2010). This thesis aims to present an evaluation methodology in the decision theory that supports the selection (choice) of a smart system.

1.2 Research problem

The problem of this research is results from the multi-criteria problem. A decision-maker often uses a tool to solve the multi-criteria problem. This chapter elaborates on the existence of multiple criteria in relation to smart buildings. After that, a selection of relevant tools is analyzed in order to find out which methods are already present to solve the multi-criteria problem.

1.2.1 Multi-criteria decision problem

According to Buckman (2014) and Arditi (2015), it is evident that the design and expected performance of buildings has changed the last few decades. When building retrofit is initiated to comply with changing demands, the decision-maker has to deal with multiple, often competing, criteria, from a wide range of stakeholders (Asadi, 2012). This is defined as the multi-criteria decision problem, otherwise known as the multi stakeholder problem. The multi-criteria decision problem forms the basis of the research.

When a decision-maker is faced with the implementation of a smart system, the same multi-criteria problem arises. This is explained using a definition by Buckman (2014), who focuses on the definition of smart buildings. Buckman (2014: p.98-99) concludes his research with a combination of smart building definitions. He summarizes the smart building concept as follows:

Smart Buildings are buildings which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at its core, in order to meet the several stakeholder drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction.

What this shows is that the smart building concept focusses on different facets of a building and includes multiple drivers, or in other words, multiple criteria. Not only is the implementation of smart systems a multi-criteria problem, the smart systems themselves are also (increasingly) complex and contain innovative hard- and software. Secondly, the implementation of a smart system often involves a series of stakeholders. A smart system is able to address a whole range of design, managerial and organizational criteria from different stakeholders (Arditi 2015). Based on the multiplicity and complexity of the criteria involved with smart buildings, the multi-criteria problem is likely to occur.

1.2.2 Problem analysis

When the decision-maker cannot decide based on their own judgement and experience, they need to have an analysis tool to aid them in this process (Anderson, 2016). The situation is often too complex to effectively solve based on judgement and experience alone. Therefore there is the need of an appropriate decision model to support the decision-making in a multi-criteria problem.

Existing literature is analysed in order to find such decision models. This chapter contains a categorisation of previous research regarding multi-criteria problems in the built environment. This categorisation is necessary to assess if an appropriate model does exist because if not, an appropriate model should be designed.

In order to find appropriate models, the existing literature needs to comply to certain aspects in order to fit the purpose of this research. The purpose of this research is to support decision-making for the implementation of a smart system in a building. This purpose is future-oriented as it tries to improve a building in the future.

The second aspect is to find a model that supports the decision-making process in assessing the optimal solution, which is ultimately the decision recommended to be made. The aim of achieving the best feasible solution is a requirement that is to be followed to the greatest extent possible, either by minimization or maximization (Binnekamp, 2014).

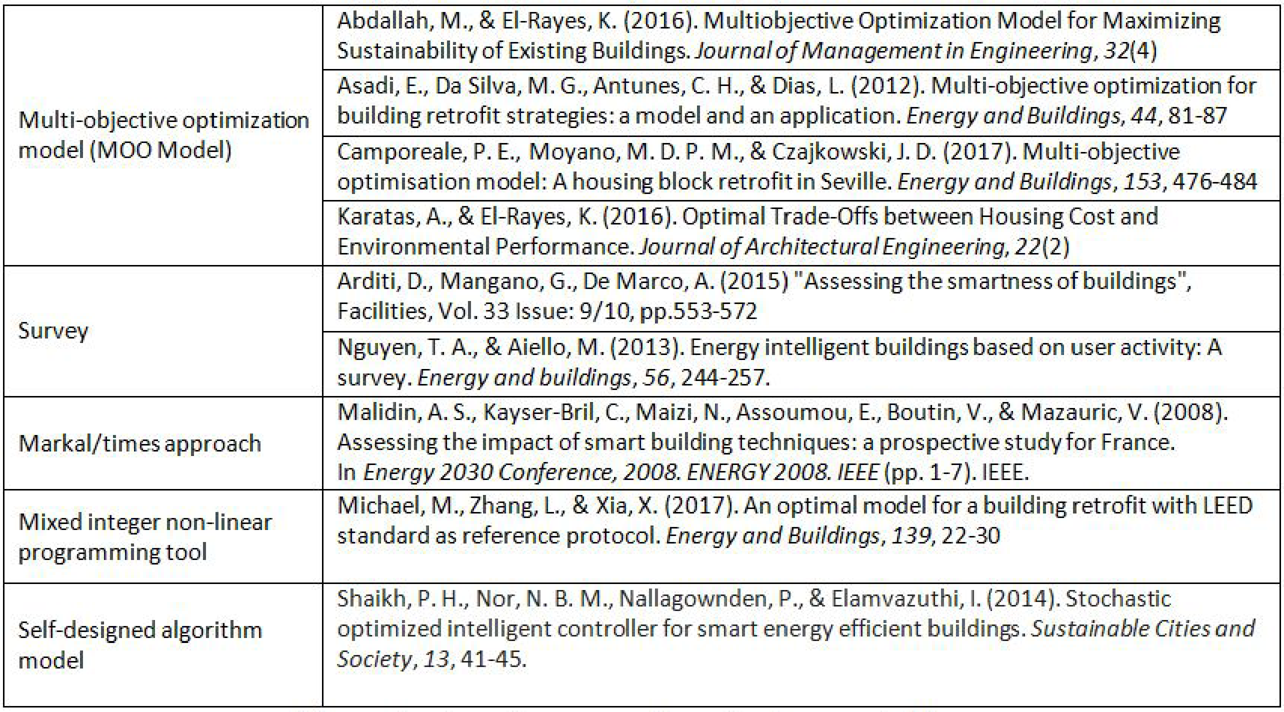
The third aspect is the inclusion of all stakeholder criteria. A multi-criteria problem is a trade-off between often competing values and bringing the value of different perspectives into focus (Asadi, 2012). Den Heijer (2011) distinguishes four main perspectives of adding value: strategic, functional, financial and physical. The perspectives of adding value contain both quantitative and qualitative values. If the best solution is ought to be found, all perspectives need to be taken into account. In other words, the model should allow the possibility to include quantitative and qualitative values from different perspectives.

The subject of this research is smart buildings. The process of making a building 'smart' is the implementation of hard- and software measures in and around the building (Buchman, 2014). It is essentially the upgrade of an existing or new building. A similar process is that of implementing sustainability measures and, according to Arditi (2015), smart buildings can be considered part of the sustainability effort. To extend the search of appropriate research, analysis tools for sustainable building retrofit are also included.

Based on these three aspects and the building retrofit scope, several search queries were created. The search query is summarized below:

- Predict OR Simulate OR model*
- Decision-making OR Decision* OR Choosing OR Choose*
- Optimization OR maximization OR minimization OR "decision-model*" OR "mathematical model*"
- "Added value" OR Value OR feasibility
- Multi-criteria OR Multi-stakeholder OR Multi-objective
- "Smart building*" OR "smart office*" OR "smart real estate". To expand the search to find other interventions these search terms were also included: "Green architecture" OR "Green building*" OR "green office*" OR "Green real estate" and "Building retrofit" OR "Building renovation" OR "Building upgrade".

Out of the search, a list of nine interesting research papers came forward (see figure 1.1). After going through them, the papers were categorised in terms of approach. Five approaches were found: Multi-objective optimization model including pareto rank, Survey, Markal/times approach, Non-linear programming tool and self-designed algorithm.



Multi-objective optimization model (MOO Model)	Abdallah, M., & El-Rayes, K. (2016). Multiobjective Optimization Model for Maximizing Sustainability of Existing Buildings. *Journal of Management in Engineering*, *32*(4)
	Asadi, E., Da Silva, M. G., Antunes, C. H., & Dias, L. (2012). Multi-objective optimization for building retrofit strategies: a model and an application. *Energy and Buildings*, *44*, 81-87
	Camporeale, P. E., Moyano, M. D. P. M., & Czajkowski, J. D. (2017). Multi-objective optimisation model: A housing block retrofit in Seville. *Energy and Buildings*, *153*, 476-484
	Karatas, A., & El-Rayes, K. (2016). Optimal Trade-Offs between Housing Cost and Environmental Performance. *Journal of Architectural Engineering*, *22*(2)
Survey	Arditi, D., Mangano, G., De Marco, A. (2015) "Assessing the smartness of buildings", Facilities, Vol. 33 Issue: 9/10, pp.553-572
	Nguyen, T. A., & Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. *Energy and buildings*, *56*, 244-257.
Markal/times approach	Malidin, A. S., Kayser-Bril, C., Maizi, N., Assoumou, E., Boutin, V., & Mazauric, V. (2008). Assessing the impact of smart building techniques: a prospective study for France. In *Energy 2030 Conference, 2008. ENERGY 2008. IEEE* (pp. 1-7). IEEE.
Mixed integer non-linear programming tool	Michael, M., Zhang, L., & Xia, X. (2017). An optimal model for a building retrofit with LEED standard as reference protocol. *Energy and Buildings*, *139*, 22-30
Self-designed algorithm model	Shaikh, P. H., Nor, N. B. M., Nallagownden, P., & Elamvazuthi, I. (2014). Stochastic optimized intelligent controller for smart energy efficient buildings. *Sustainable Cities and Society*, *13*, 41-45.

Figure 1.1. previous research focussed on the multi-criteria problem related to smart buildings

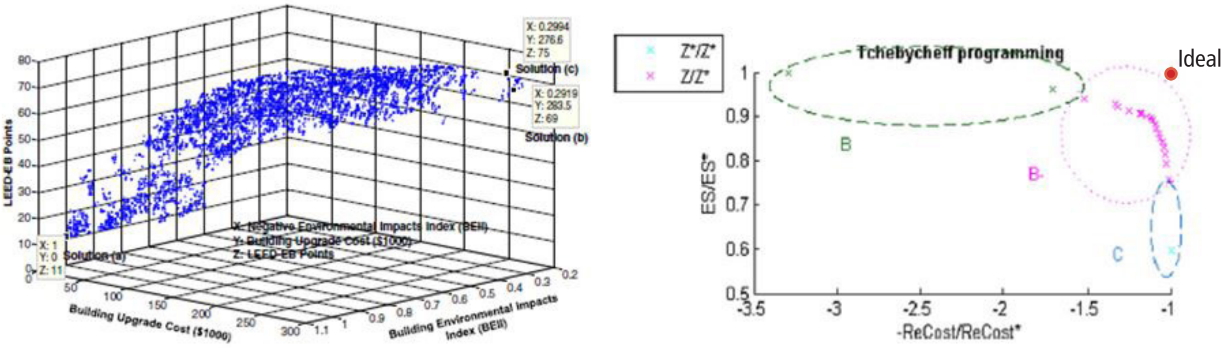
Multi-objective optimization model (MOO model)

Multi-objective optimization has been applied in many fields of science, where an optimal decisions needs to be made between two or more conflicting objectives/criteria (Asadi et al. 2012). The research of Abdallah et al. (2016), Asadi et al. (2012), Camporeale et al. (2017) and Karatas et al. (2016) all identified the problem of conflicting values and proposed a MOO model to come to an optimum for a specific situation. The relevant model design is similar for each author. The model design consists of objectives/criteria, alternatives and constraints.

All authors provided a trade-off model between conflicting objectives. Abdallah et al. (2016) identified the problem between three objectives: environmental impact, building upgrade costs and Leed points earned. Asadi et al. (2012) identified two problem objectives: energy use and costs. Camporeale et al. (2017) identified the trade-off between energy consumption and financial performance. Karatas et al. (2016) identified the problem objectives environmental performance and initial costs.

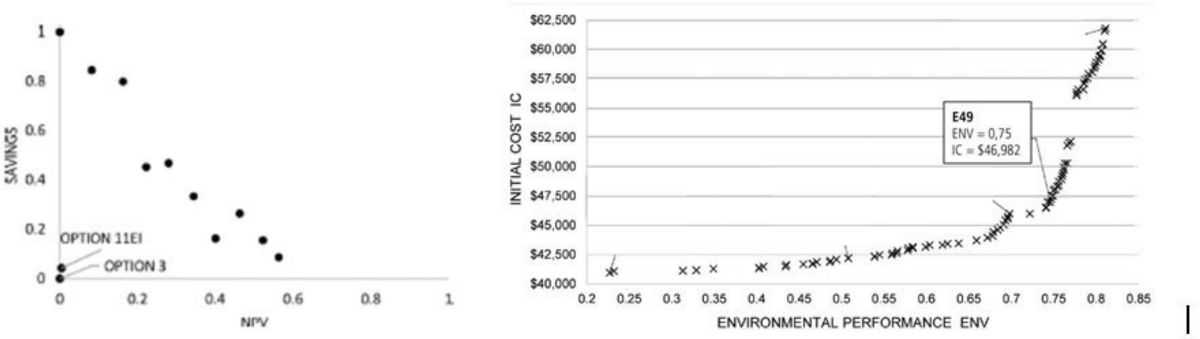
The values of the respective objectives for each alternative are calculated. The optimum to be found is the alternative that performs best on the combination of the two (or three) values.

All authors use the Pareto rank. The Pareto rank is used to plot each alternative on a graph consisting of the objectives representing the X, Y and if applicable the Z axis (see figure 1.2). The optimal alternative is the one that is closest to the ideal situation (Asadi et al., 2012). For example, Karatas et al. (2016) use the criteria environmental performance and initial costs. The ideal situation is where environmental performance is maximized and costs are minimized.



Pareto rank (Abdallah et al., 2016)

Pareto rank (Asadi et al., 2012). ES = energy savings



Pareto rank (Camporaele et al., 2017)

Pareto rank (Karatas et al., 2016)

Figure 1.2. Pareto rank of different MOO models

Secondly, some authors implement constraints to only find feasible options or to find the optimum of one objective based on the constraint of the other objective. For example, when Karatas et al. (2016) want to know what the optimum environmental performance is for an alternative not costing more than $47.000, the Pareto rank can be used. The optimum alternative is than E49 (See the Pareto rank of Karatas et al., 2016).

The MOO model is an excellent tool to find an optimum between two or three objectives. The objectives are quantitative of nature and it's not possible to include qualitative values. Moreover, the amount of objectives included is relatively low. The multi-criteria problem existing in the implementation of smart systems is much larger than three criteria and consists of both quantitative and qualitative values. Therefor the MOO model is not suitable.

Survey

Arditi et al. (2015)

The study of Arditi et al. (2015) aims to capture the perspectives of construction professionals in a classified taxonomy of the various characteristics of smart buildings and to develop an index to be able to define their level of smartness.

The variables are based on literature and a hypothesis is established. The approach of the authors is to make a survey, include all relevant variables and administrate it to construction professionals in the service of designers, constructors and owners. Each variable consisted of at least one question which included the Likert-scale. The results have been analyzed with the Kruskal-Wallis test and were used to develop a smartness index.

Persons involved are professionals and practitioners wo are members of the Construction Management Association of America. However, because the persons are not related to a specific case they are not considered to be stakeholders.

The most compelling facet of this paper are the variables included in the research. The variables are across different domains (Economic issues, Energy issues and Occupant comfort) consisting of quantitative and qualitative variables, e.g. construction costs and thermal comfort respectively.

Nguyen et al. (2013)

User activity and behaviour is considered a key element and has long been used for control of various devices such as artificial light, heating, ventilation, and air conditioning. However, the question remains how multiple users' activity and behaviour are taken into account. The purpose of this article is to give an answer to this question by studying prominent international projects on energy savings in buildings, that are based on user activity as the key element of the system.

The article is empirical as it tries to answers the question with a survey. Through the survey, the authors determine the most valuable activities and behaviour and their impact on energy saving potential. It is clear that this article does not provide a suitable model, however, it does take the quantitative nature of different stakeholders into account. It discusses the preferences of users. The variables that are taken into account are real-time occupancy information, occupant preference and activities and behaviour.

Both authors use empirical research and do not provide a model to find an optimum or best option. Nevertheless, they do include quantitative and qualitative values and explain why a smart solution may be best.

Markal/Times approach by Maladin et al. (2008)

The purpose of this paper is to develop a long-term planning model based on energy savings potential and energy conservation techniques. The model calculates the energy conservation and costs and the decision is based on what is most cost-effective. The case used in the research is the entire commercial property of France.

The approach being used is the Markal/times approach. The model is run twice: on the first run, smart building upgrades are made available to the model, on the second one they are not. All other parameters remain identical between runs. The results of both models can be compared and the difference can be studied. This way the added value of smart building upgrades can be calculated.

The input of the model are the demand figures in the period 2000 – 2050. The demand consists of heating, cooling, lighting, specific electricity uses and "other uses". The energy demand is calculated over time. Because of technological evolution it is assumed that energy use will be more efficient, which is also taken into account when putting in the energy demand. Other parameters that will be put in the model are energy prices and discount rates.

The alternatives are called Energy Conservation Techniques (ECT) and their impact on energy reduction is based on publications of the European Insulation Manufactures Association (EURIMA) and the research of Schneider Electric's.

An upper limit is implemented in the model so as to prevent unrealistic moves by the model. It is expected that one ECT is not applicable to all commercial properties.

The output of the model shows how much energy can be saved and how much costs this could save. It simulates situations based solely on quantitative input and focusses only on saving energy and costs. It is capable of including other quantitative values but not qualitative values. Moreover, it predicts the optimum for a portfolio of buildings rather than one building.

Integer non-linear programming tool by Michael et al. (2017)

The authors state that the selection of facilities to be replaced during a building retrofit is challenging due to conflicting interests and a wide range of criteria. In order to assist the decision-maker, the authors present a multi-objective optimization model aiming at optimizing retrofitting costs, energy savings, water savings, payback period and points earned under the Leadership in Energy and Environmental Design (LEED) rating system.

The approach being used is that of operational research including a mathematical model that is developed based on the problem presented. The model developed is a mixed integer non-linear programming (MINLP) tool. The optimization results show the optimal number of selected facilities and measures that result in the minimum retrofitting costs, maximum LEED points and the minimum discounted payback period (DPP).

The input for the model are decision variables, objective functions and constraints. The decision variables are alternatives for energy and water savings within an existing building. The alternatives consists of measures in existing facilities or placing new facilities. Each alternative is tested on predefined objectives, which are minimizing retrofitting costs, maximizing LEED points and minimize DPP. For the practicality of what can be feasibly achieved, the model contains criteria to which the alternatives need to comply. These constraints are budget and minimum requirements regarding LEED points in different areas.

The output of the model is achieved using the weighted sum method in which the original objectives are transformed into a single objectives. The aggregated objective function is:

$J = w1F1(x) + w2F2(x) + w3F3(x)$

w = the weight for each criteria. F = the formula belonging to the respective criterion

The objective functions are combined into one scalar function by applying constant weighting factors. These weighting factors can vary and is the choice of the DM. Based on the weight given, an optimum is found and the quantity for each objective function is given. Based on the models formulas and weight different options can be compared.

However, the objectives are quantitative values and it is not possible to include qualitative values. Secondly, the values are predefined by the authors and are fixed. The formulas are specifically made for these objectives.

Self-design algorithm by Shaikh et al. (2014)

A challenging task of the building control is to achieve interior building environment comfort with high energy efficiency. The authors developed a multi-agent (multi-stakeholder) control system to simulate effective management of energy and consumer comfort.

The approach used is a specifically designed multi-objective algorithm with the prime goal to maximize comfort while minimizing the power consumption. Comfort is calculated under various conditions with coefficients weighted by the consumer. The general strategy of the model is to find a trade-off between the two conflicting objectives.

The input are the parameters for the specifically designed formulas. For comfort, the parameters are temperature, illumination and indoor quality (co2 concentration). The formula also included the human behaviour patterns for each of the parameters (ethermal , elux , eco2) and the weight of importance for each parameter (see formulas below).

$$Comfort = \partial_1 \left[1 - \left(\frac{e_{Thermal}}{Temp_{set}}\right)^2\right] + \partial_2 \left[1 - \left(\frac{e_{lux}}{Lux_{set}}\right)^2\right] + \partial_3 \left[1 - \left(\frac{e_{CO_2}}{AQ_{set}}\right)^2\right]$$

$$Overall \quad comfort = \sum_{i=1}^{n} w_i \cdot comfort_i$$

A series of three formulas is developed for the power demand (see formulas below). Each formula calculates the power demand for temperature, illumination and indoor quality based on the activities in a building. The formulas are determined in previous works of the author.

- Pt = 5,665 x Tt +2,961 for power required for temperature
- Pt = 4,428 x sin(0,9603 x IL – 0,423) for power required for lighting
- Pw = 9,444 x e(Waq – 1163/389)2 for power required for the air quality control

The developed model is used in the building to actively optimize comfort and energy demand. There are no alternatives to be evaluated. Instead, the authors simulate the situation where comfort and power consumption is regulated with and without the algorithm. The output is two graphs for both power consumption and comfort against time with and without the algorithm in place.

The researchers provide a useful method to establish an optimum algorithm for a situation with conflicting values. However, the approach is not focussed on a multi-criteria problem and all parameters are quantitative only.

Criteria of all papers

Over the years Den Heijer (2011) elaborated on different stakeholder perspectives distinguishing four main perspectives of adding value: financial, sustainable, strategic and functional. The four perspectives could be used to place the criteria of all analysed papers (see figure 1.3).

The two main perspectives in the analysis are financial and sustainable. Abdallah et al. (2016), Asadi et al. (2012), Camporeale et al. (2017), Karatas et al. (2015), Maladin et al. (2015) and Michael et al. (2015) provide an approach to optimize between financial performance and energy. Financial performance is either expressed in costs or in financial gain. Energy is expressed in savings or consumption. The article of Abdallah et al. (2016) and Michael et al. (2015) also include the LEED-EB point system for the sustainability perspective. LEED-EB is the Leadership in Energy and Environmental Design for Existing Buildings rating system. It is an green building rating system consisting of variables such as waste, energy consumption, materials and resources, indoor environmental quality and innovation in operation. All values of these articles are quantitative.

The article of Arditi et al. (2015) takes all four perspectives into account and include both quantitative and qualitative values. Most emphasis lies on financial, sustainable and strategic. However, the Author does not provide a model to find an optimum for improving in a future situation.

Nguyen et al. (2015) and Shaikh et al. (2015) focus on the strategic and sustainable perspective. Both authors analyse the conflicting function between energy savings and occupant comfort. Shaikh et al. (2015) developed an algorithm to find to optimum between the two values. The values of both authors are only quantitative.

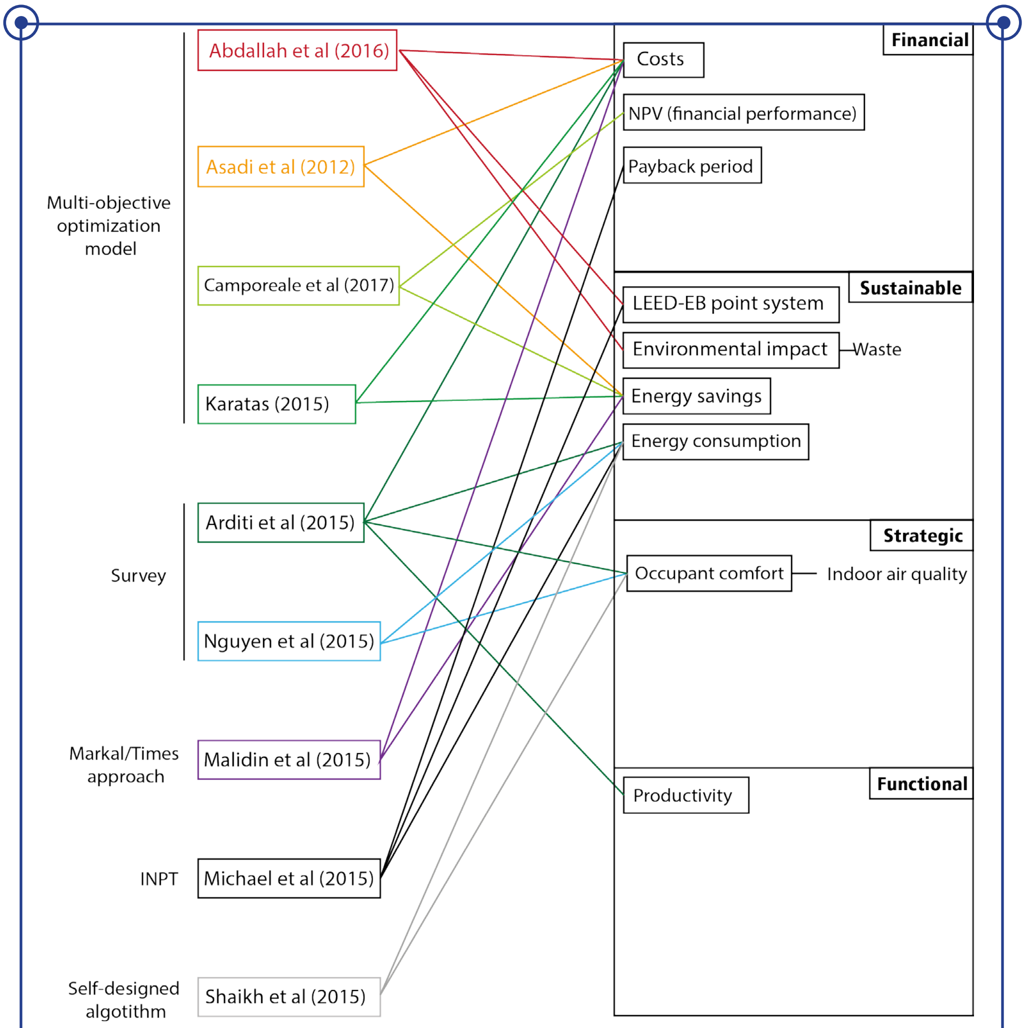
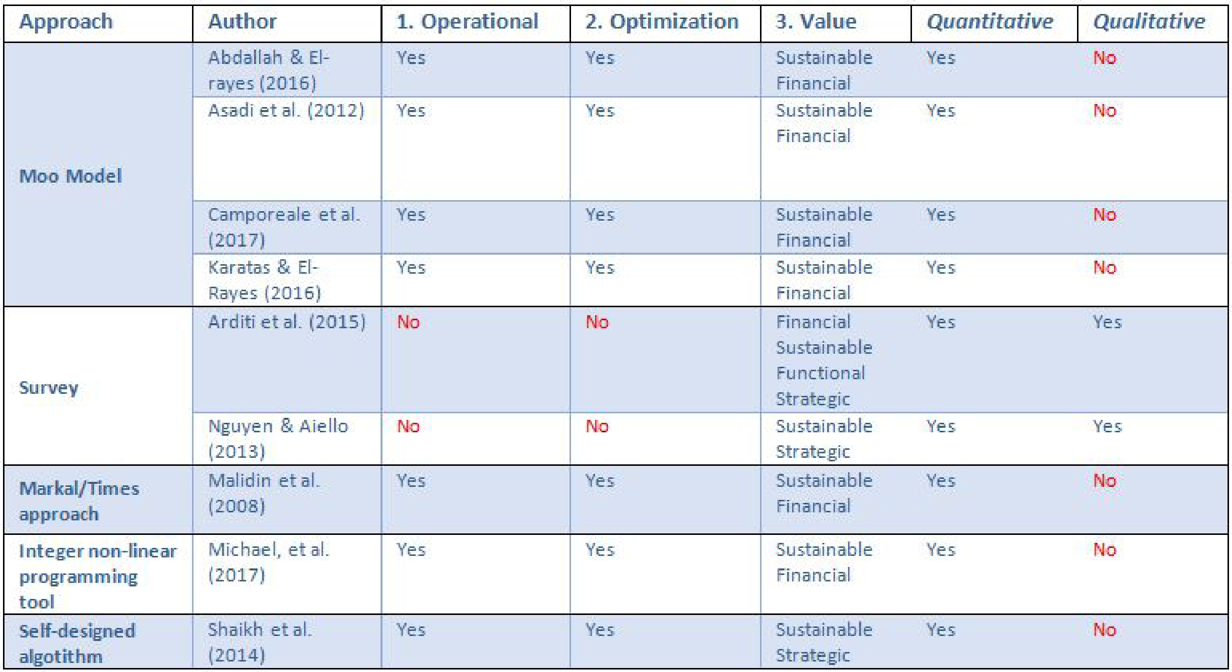


Figure 1.3.Criteria of previous research placed in the four perspectives of value (based on Den Heijer, 2011).

1.2.3 Problem statement

Based on the analysis of nine articles a statement can be given on the usability of existing decision models in the field of smart buildings and building retrofit. An appropriate model should be operational by aiming to improve a building in the future. Secondly the aim of the model should find or design the optimum or best option to choose. Third, the model should be able to make a trade-off between conflicting quantitative and qualitative values. Moreover it should be possible to include a high number of both quantitative and qualitative values.



Approach	Author	1. Operational	2. Optimization	3. Value	*Quantitative*	*Qualitative*
Moo Model	Abdallah & El-rayes (2016)	Yes	Yes	Sustainable Financial	Yes	No
	Asadi et al. (2012)	Yes	Yes	Sustainable Financial	Yes	No
	Camporeale et al. (2017)	Yes	Yes	Sustainable Financial	Yes	No
	Karatas & El-Rayes (2016)	Yes	Yes	Sustainable Financial	Yes	No
Survey	Arditi et al. (2015)	No	No	Financial Sustainable Functional Strategic	Yes	Yes
	Nguyen & Aiello (2013)	No	No	Sustainable Strategic	Yes	Yes
Markal/Times approach	Malidin et al. (2008)	Yes	Yes	Sustainable Financial	Yes	No
Integer non-linear programming tool	Michael, et al. (2017)	Yes	Yes	Sustainable Financial	Yes	No
Self-designed algotithm	Shaikh et al. (2014)	Yes	Yes	Sustainable Strategic	Yes	No

Figure 1.4.Research analysis

Plenty of research aims to find an optimized balance for a future situation. When doing so, conflicting values are taken into account such as minimum costs vs. maximum environmental performance or minimum energy use vs. maximum comfort. However, none of those models provide the possibility to include qualitative values. The only articles that include qualitative values do not provide an operational model that aims to optimize.

Moreover, the amount of criteria that is taken into account is rather low. Most research focusses on only a maximum of two or three criteria. In theory that is a multi-criteria problem, however the aim of this research is a wide range of criteria, not limited to a maximum.

Most research limits to two perspectives. The values are mostly financial, sustainable and to a lesser extend strategic, which only includes occupancy comfort. Values within the functional perspectives are hardly ever mentioned.

In conclusion, previous research provides models that are capable of predicting the optimized value for two or three conflicting quantitative values, but fail to incorporate qualitative values. In the built environment, qualitative values are an important part of the added value of an intervention such as smart systems. Therefore, none of the existing models are sufficient in predicting the overall added value.

1.2.4 Why is this a problem?

As mentioned before, the decision maker seeks aid of analysis when the situation is complex and consists of a wide range of criteria. In order to consider all criteria, the model should offer the possibility to do so. It may be possible that these criteria are qualitative (subjective). The output, the recommendation for the decision-maker, is simply the projection of the input that is taken into account (Anderson, 2016). If for instance the best system regarding price vs. energy reduction is ought to be found, plenty of previous research models are sufficient. If the best system for all stakeholders (overall value) needs to be found, the model must be capable of taking all types of criteria into account. If not, the outcome will not project what would happen if the decisions occurred in the real situation (Anderson, 2016). It will project what would happen if only these criteria occur, which is only part of the real situation.

1.3 Research question

The aim of my research is to extend this existing line of research and incorporate the possibility to include both quantitative and qualitative criteria in a predictive model. The model can be used to predict the added value of the implementation of a smart system in a building. In this thesis, the value of a building is measured using the preference of the stakeholders, which will be explained in detail in the theory and method chapter. The thesis will give an answer to the following research question:

How can a decision model predict the added value of a smart system?

The research question considers a multi-criteria problem and takes all stakeholders, representing different perspectives, into account. The model is going to be designed to support the decision-maker in the effort to choose the best smart building. The requirement for answering this question is to integrate the preferences of the stakeholders and the weight of each preference.

The answer to the research question will be, strategical, technical and practical. The strategic answer focusses on the process; how the decision model is created and how the prediction of the added value comes about. The technical answer will focus on the alternatives; which alternatives are there to be considered and how does each system work. The practical answer focusses on the product (the mathematical model); how does the model work in this case and how can it be used in other cases.

Sub questions

To derive at an answer, the critical elements of my research are the composition of the decision model, the selection of design alternatives (smart systems) and the preferences of the stakeholders. The critical elements can be divided in demand and supply. The demand side consists of the variables, preferences and weights of the stakeholders which make up the parameters of the model. The supply side are the design alternatives. The following sub-questions should gain insight into the critical elements of this research:

1. Demand: Which parameters need to be present in the decision-model?

2. Supply: Which relevant design alternatives can be made based on existing smart technologies?

The term 'relevance' is of importance and needs to be elaborated on before answering the second question. The supply side consists of a comprehensive amount of options. An inventory of smart systems will give insight into the supply of smart systems. Subsequently, the list of interventions needs to be narrowed down based on the aim of the redevelopment. To do so, additional sub-questions are added:

2.1 What smart systems are present today?

2.2 What smart systems suit the aim of organisation?

1.3.1 Scientific relevance

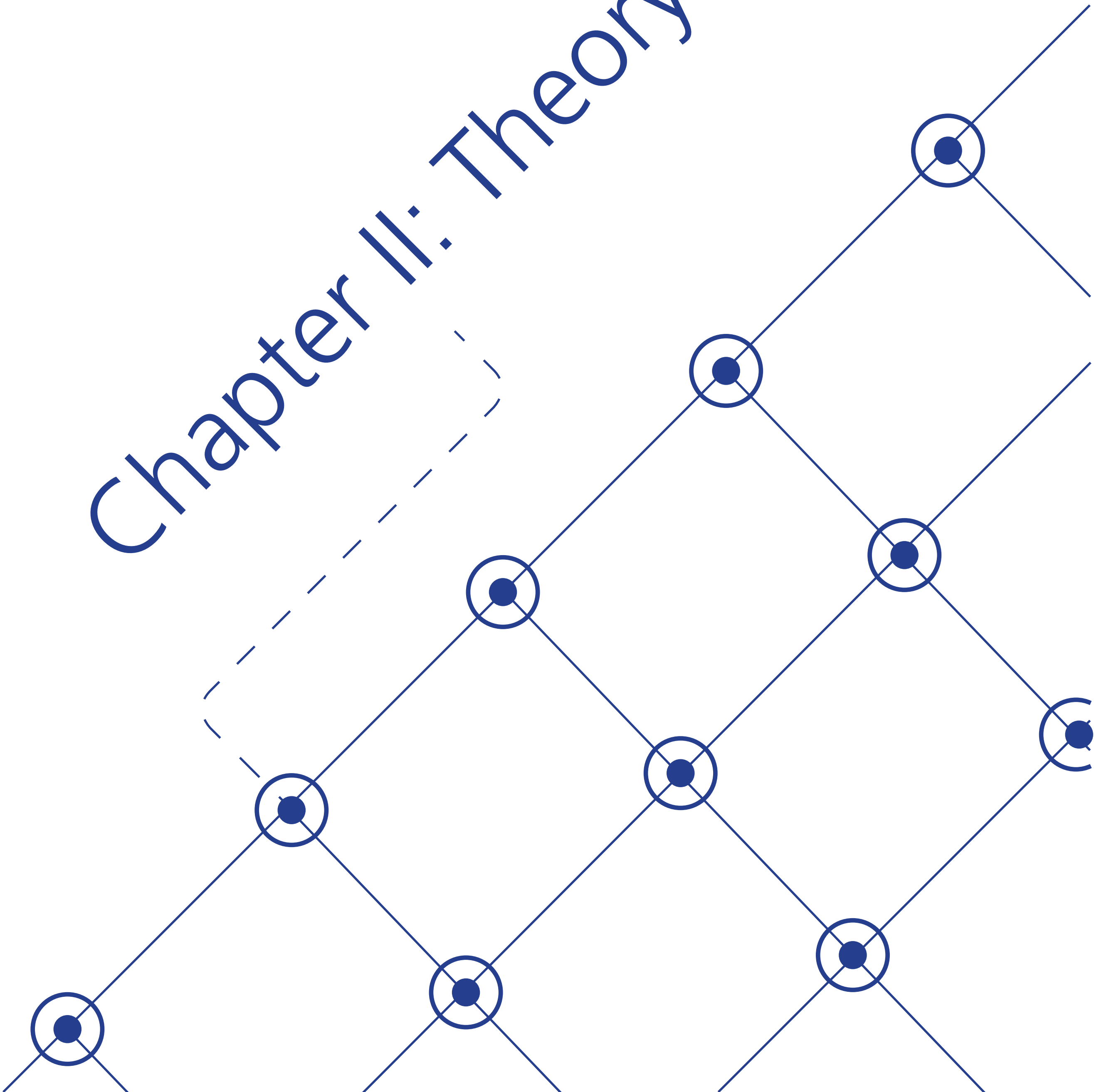
Decision theory that is applicable when a set of multiple design alternatives are presented is called 'design space'. Design space is a mental construct of an intellectual space that envelops or incorporates all of the potential solutions to a design problem (Dym & Little, 2004). A mental construct that is used within this domain is simulation. Simulation using a mathematical decision model is a scientific approach to predict your optimum. It must be noted that most of the authors concluded that such models are never 100% accurate. The primary concern during simulation is that the modeller is never sure if the model accurately project a true situation (Anderson, 2016). Researches such as Asadi (2012), Kim & Kim (2017) and Abdallah (2016)—who all developed a mathematical model to support decision making—state that their model is a simplified version of reality. Therefore, an important part of the research is the process of building an accurate model and the lessons learned on the use, evaluation and validation of the decision model.

The second scientific contribution of this research is the process of matching demand and supply in the field of CREM. In the built environment, demand changes constantly while on the other hand the supply side is also subject to deterioration (de Jonge et al., 2009). In the field of CREM, extensive literature is written about strategies, methods and models to support the process of matching demand and supply. In practise, decision-makers develop an intelligent combination of methods and instruments available in order to create the best possible solution (de Jonge, 2009). Even so, this research also is a combination of methods. Based on existing literature, a model will be developed to support decision-making in a multi-criteria problem. This model could be used for other decision-making problems as well.

1.3.2 Societal relevance

The improved economic conditions in the Netherlands have stimulated the real estate market. Due to the well performing market, as well as the trend to transform offices into other use, the vacancy of the office market strongly decreased (JLL, 2017). In quantitative terms, the amount of real estate in the Netherlands offers enough space until 2030 but in qualitative terms the supply is lacking (CPB, 2017). CPB also concludes that in the recent years, a limited amount of new supply has been added to the market and a large number of existing buildings fail to meet the changing demands. Simultaneously, the user requirements of real estate have changed towards smart and sustainable buildings; buildings that, with the use of innovative technology, provide higher performance (Kejriwal, 2017). We already see a lot of smart solutions in buildings today and it is expected to play an increasingly important part in society. The research could serve as a reference for the upscaling of smart systems in the built environment.

Chapter II: Theory



2. Theory

The research question can be divided into four parts: smart buildings, added value, decision model and stakeholders. Relevant literature of each of these parts is included in this chapter.

2.1 Smart Building

2.1.1 Definition

Although there is an increasing amount of academic, popular and business literature addressing Smart Buildings as a concept, it is still a relatively new implementation to the real estate sector (Buckman, 2014). The concept is still evolving and so are the many definitions of smart tools and smart buildings. Valks et al. (2016: p.11), in his PhD research at the TU Delft, describes a smart tool as the following:

"A service or product which collects (real-time) information to improve the use on the current building on the one hand, whilst supporting decision making on the future use on the other hand".

Buckman, (2014: p.98) described the definition of smart systems in relation to real estate:

"Smart Buildings are buildings which integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at the core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction. The increased amount of information available from this wider range of sources will allow these systems to become adaptable, and enable a Smart Building to prepare itself for context and change over all timescales".

Arditi, (2015: p.554) describes a smart building as:

"A building that involves the usage of design solutions and technology to develop facilities that is comfortable for their occupants while at the same time economical for their owners".

Every researcher has its own definition of smart building but they all agree on certain points. (1) Smart buildings collect and aggregate information. (2) The smart system is capable of adapting the performance of the building for current and future use. (3) Smart buildings is a multi-criteria and multi-stakeholder concept.

2.1.2 Smart building elements

One thing is the wide amount of definitions regarding smart technology and smart buildings, the second is how this comes about in practice. Every smart system consists of different elements, both hardware and software. Based on existing literature about smart buildings four elements can be found.

- Sensors
- An integrated platform
- Internet-enabled devices
- Building facilities

Sensors

In a smart building, different information such as temperature, humidity, light and sound, presence and movement can be collected from sensors and transferred to the building control system (Arditi, 2015). Many sensors exist such as infrared, cameras, Bluetooth, Wi-Fi, Ultra-wideband, CO2, security gateways, utility meters, thermostats, smoke and pressure sensors (Valks, 2016 & Kejriwal, 2016). They are placed throughout the building, connected with each other in a grid and linked to the integrated platform.

Integrated platform

The main body of the grid is the integrated platform where all the data is stored and saved. Structured and unstructured data from different internal and external sensors can then be aggregated through a common platform. Additionally, information can also be gathered from external sources such as weather or traffic forecasts. The aggregated information can be analysed with different analytical tools and approaches (Kejriwal, 2016). Without this process, the sensors would be useless. It is the ability to process, analyse and learn from all the data that make a building smart (Nouveau, 2017). This can be seen as the brain of the smart system.

Cloud computing is the innovative technology that promised reliable and virtual storage and saving of all data collected by sensors (Gubbi, 2013). Cloud computing has enabled applications to scale dynamically to support millions of users to store their data. Cloud platforms can be accessed by anyone with a web browser and an Internet connection (Suram et al., 2018). Cloud computing eliminates the purchase of expensive processors and makes it possible to move many types of engineering, scientific, and HPC applications and workflows into the cloud. This has opened up new opportunities for creating novel scientific, data management, analysis, and visualization applications that leverage the performance capabilities offered by cloud computing (Suram, 2018). This technology was an important factor in the existence of smart buildings. Due to the availability, it is now possible to securely save all data generated in a building and manage, analyse and visualize data real-time and historical.

In order to access the data in the cloud a link needs to be established. The link between applications and the cloud is called the Application Programming Interface (API) (Suram, 2018). The API is an extra piece of software programmed to access the cloud from anywhere. An open cloud platform has the ability to give access to all kind of applications and the owner of the data is capable of exporting the data for other use. The analysing and visualizing of the data does not happen in the cloud but is done using specially designed applications, which connect to the platform. Thus in order to provide useful information, for example occupancy of the building, it is important that the application interface can be connected using an API.

Internet-enabled devices

The internet-enabled devices are tools to connect with the integrated platform via applications installable on the device. It is a tool for input in order to change building operations or give certain information and output in order to request information from the database. This is done on the interface of the application. Interface applications provide a wide range of functionalities and features, which are different from one another to help users get insight into relevant information (Schmeck, 2017). The interface is a software program, which can be created freely and customized by developers. The interface application receives the data from the cloud through an open API and based on predefined algorithms the data is transformed into useful information (Schmeck, 2017). The interface of smart buildings transforms the data into understandable information, often visualized in 3D models, building plans, graphs and infographics.

The use of these applications also generates a new set of information. An example of such applications is that of the test case of the Outlook (Nouveau, 2017). They developed a smart building application accessible by any internet-enabled device in which you can adjust the indoor climate in order to increase the quality of space (input), but also to request information about occupancy (output). Furthermore, all information is stored so it can be analysed to further improve the building and predict maintenance.

The information that is shown to the user of a smart building application can be categorized on three levels: historical, real-time and predictive.

Historical information is aggregated data from a defined period in the past. By taking advantage of data history, it is possible to identify data patterns that get insight and define the standard behaviour of the building and its users (Linder, 2017). Different sets of historical data can be compared to show inefficiencies and support assumptions. The aggregated information can be analysed using different tools to develop descriptive, prescriptive, and predictive insights for building operations teams (Kejriwal, 2016). For example, the occupancy of a building throughout the last year. Based on this data a building manager can see if the building is too big or small for the company or to support his assumption that on Friday office is 'half empty'.

Real-time information is data that is being monitored at the moment the application is accessed. Sensors help track the location and movement of people and items, which can be visualized on a real-time basis (Kejriwal, 2016). Moreover, the user may be able to change settings real-time by connecting through the application with the smart system. For example, when finding a free workplace, the user can log in to the application and find an overview of the office. On the interface, real time information about which desks are used is displayed. Subsequently the user could click on a free desk to receive specific information and book the workplace. However, there is always a delay between real-time data and the actual situation due to communication time and update rates. The real-time information is always a bit distorted.

Predictive information is forecasting situations based on real-time and historical data. External and internal data sources can be used to predict what is likely to happen. Similar to historical data, by identifying data patterns, future behaviour of the building and users can be predicted (Linder, 2017). Predictive information will always be subject to uncertainty but it is assumed that by self-learning algorithms the uncertainty could be mitigated. For example, based on the historical data of the occupancy level every Monday from the last half year, the smart system can predict the occupancy for the upcoming Monday. In combination with agendas, room bookings, vacation schedule and weather forecasts, the prediction is further improved. Predictive information is often a combination of different real-time, historical and other predictive data.

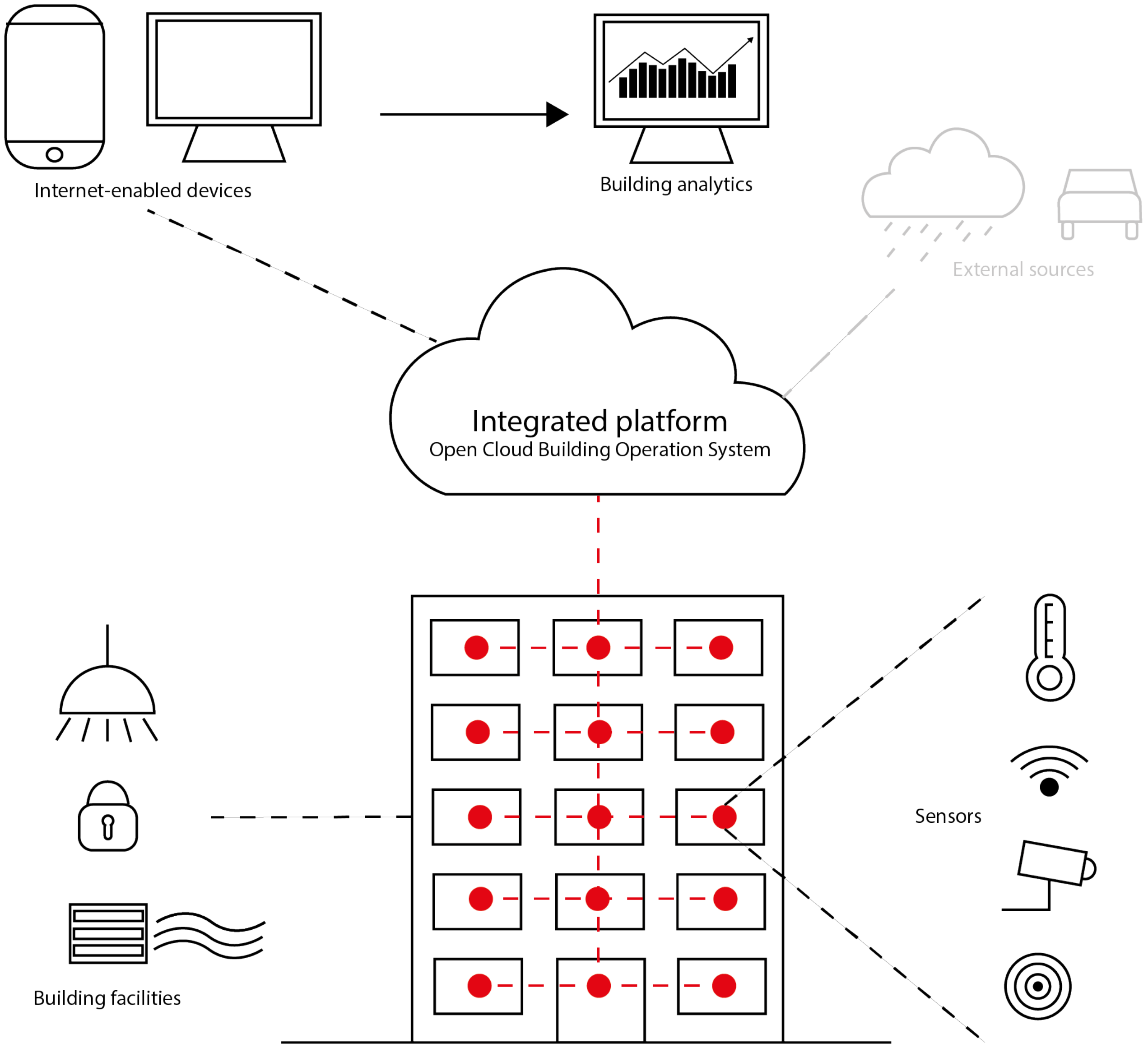


Figure 2.1. Integrated smart building

Building facilities

The building consists of a variety of installations controlling things such as the indoor climate, facade, space, lighting, entry/exit points etc. The information from the integrated platform can be used to change the operation of these installations on the three levels of smartness (Buckman, 2014). On the lower level of smartness, information is used to change the operation of the building installations (reactive). On a higher level of smartness, building operations is defined with the use of the data (adaptive). On the upper bound of smartness, building operation is defined based on predicting the future operation.

In order to change the operation of building facilities the platform needs to be connected to the facility directly or the Building Management System (BMS). BMS systems are "Intelligent" computer-based control system installed to monitor and control a buildings technical systems and services such as air conditioning, ventilation, lighting and hydraulics (Smith, n.d.). BMS systems have their own communications protocols so in order to connect the BMS to the integrated platform the data needs to be translated. If so, the data can be used to improve building facilities. For example, when a sensor measures the temperature, humidity and CO2 levels, the BMS receives this data, recognizes a difference between desired and real air quality and responds to it by changes the operation of the building facilities, reactive, adaptive and/or predictive (Buckman, 2014).

This element is only included in the smart system if a communication protocol is made and data is shared through open API. Otherwise, this element functions separately.

2.1.3 Scope

Smart building is a broad concept with many different functionalities (Ven, 2017). In this paragraph, the two most popular techniques are addressed: indoor positioning and indoor climate.

Indoor positioning techniques determine the position of an object or a person (Mautz, 2012). The purpose of indoor positioning is to get insight, define the standard behaviour of the building and its users, and support user activities in de building (Linder, 2017 and Kejriwal, 2016). The fact that everyone has a smart phone and wireless technology is present in almost every building spurred the development of indoor positioning techniques (Luo, 2017). Due to the rapid increase of these two elements, the indoor positioning market is estimated to have a value of $5 billion by the end of 2018 (Luo, 2017). For these reasons indoor positioning is one the most interested techniques within the smart building concept.

The second techniques is indoor climate. Indoor climate techniques focus on measuring the quality of the indoor environment. Measuring the indoor climate is a popular technique because studies found that bad indoor air quality could decrease workspace productivity by more than 50 percent, while increasing the average sickness absence rate by up to 52 percent (Allen et al., 2016). If you improve office air quality, you improve employee mood, health and productivity (Allen et al., 2016). Secondly, indoor climate techniques can give insight in the energy consumption and use this information to improve the sustainability of the building. For instance, the study of Maladin (2008) shows that smart building solutions can bring sizeable energy savings, on average 8% in the French commercial sector.

The primary scope of this research is indoor positioning. The reason for this is to align with the scope of the case. In short, the problem related to the case is the lack of insight in building use, occupancy and problems in wayfinding. The scope of the case will be explained in detail in the introduction of the case. From this point on, indoor positioning is the main focus.

Indoor positioning of a smart building

Based on multiple meetings with smart system companies and experts, a basic framework for indoor positioning systems is developed. The basic framework consists of seven elements. Each of the elements is explained and visualized in figure 2.2.

1. Sensing. This is the primary source of data. Data is collected by placing sensor nodes (hardware) throughout the building. The sensor nodes either communicate with a mobile device or sense a person. The sensor nodes that communicate with a mobile device commonly use Wi-Fi, Bluetooth Low Energy (BLE) or VLC. The nodes that sense a person commonly use Infrared (IR), electromagnetic sensors or a camera. In appendix 1, each sensing method is explained.

2. Power. The sensors need to be supplied with energy. Three methods are common in the field of smart buildings: AC/DC power network, Powered over Ethernet (PoE) and battery. Each method is explained in appendix 2.

3. Communication. The data that is collected needs to be pushed to a secure and spacious data center to be saved and stored (Gubbi, 2013). The communication can be directly from the sensor node or it can go via a gateway (Gubbi, 2013). The gateway forms a bridge between the sensors and an existing internet network. Communication methods that are common in combination with a gateway are Wi-Fi, BLE, Zigbee and Ethernet. Direct communication is commonly done by LoRa or 3G/4G. See appendix 3 for the explanation of each communication method.

4. Infrastructure. Almost every office building has an existing wired and wireless communication network, most commonly Wi-Fi (wireless) and Ethernet (wired). Outside of the building there are also wireless networks, such as the 4G network throughout the Netherlands and a LoRa network in most parts of the Netherlands.

5. Software platform. As explained in the previous paragraph, this is where the data is saved and stored. The platform contains intelligent algorithms in order to translate the data into useful information. Secondly machine learning methods based on evolutionary algorithms, genetic algorithms, neural networks, and other artificial intelligence techniques are necessary to achieve automated decision making (Gubbi, 2013)

6. Interface. Visualization is critical for an IoT application as this allows interaction of the user with the environment (Gubbi, 2013). With recent advances in touch screen technologies, use of smart tablets and phones interfaces have become very intuitive. As technology moves from 2D to 3D screens, more information can be provided to the user in meaningful ways for consumers (Gubbi, 2013). The visualizations are stored in the platform and accessible by the use of an application.

The use of the application creates a second source of data.

7. Buildings analytics. Similar algorithms analyses all data that has been coming in to the platform and visualize it into understand information. By taking advantage of data history, it is possible to identify data patterns that get insight and define the standard behaviour of the building and its users (Linder, 2017). The aggregated information can be analysed using different tools to develop descriptive, prescriptive, and predictive insights for building operations teams (Kejriwal, 2016). The most common example is a dashboard. A dashboard is an online platform, which provides insight in the data. It can be programmed according to the wishes of the client.

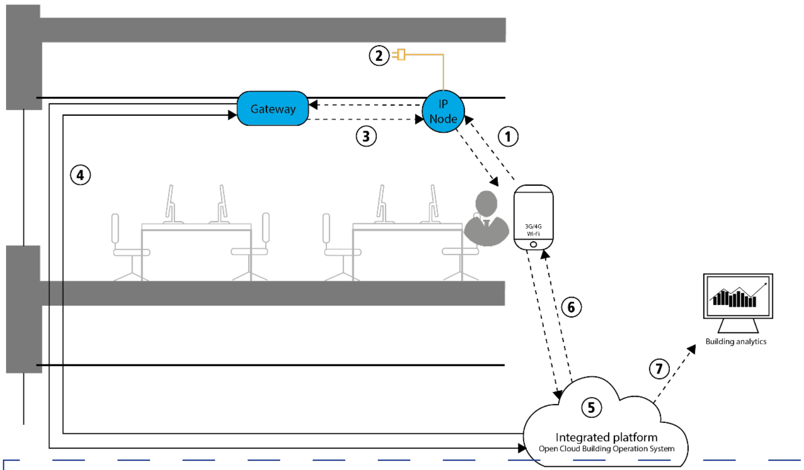


Figure 2.2. conceptual model of an indoor postioning smart system

2.2 Stakeholders

The aim of this research is to include all stakeholders. Stakeholders are people with an interest in the project. The decision-maker is a person that approves or disapproves the selection from available options and may be limited to only one stakeholder. In this research, a decision-maker is a stakeholder but not every stakeholder is a decision-maker. Relevant stakeholders are case specific and will be explained in the stakeholder selection. In this paragraph, the relation between smart and stakeholders will be explained.

Smart Buildings are occupant-based (Buckman, 2014). They collect their data from building users and internet enabled devices. Many of these internet-enabled devices are owned and operated by a user. The user of the building is the most essential stakeholder for the performance of indoor positioning. Almost all functionalities are focussed on the user, some actively empowering the occupants to make their own decisions within the smart systems and other passively measuring the position, routing and activities of the user. The tenant and its users are always part of the use of a smart system.

Smart buildings integrate physical aspects such as materials, installations and construction (Buckman, 2014). Based on indoor positioning technology aspects of the building can be adapted and controlled. Based on fact that an indoor positioning system has to be integrated in the building the owner of the building has interest in the implementation.

Smart system integration is also a financial case. In the problem analysis, the financial aspect is mentioned as a decision variable 10 out of 12 times. The other two articles mention costs as variable but do not include it in the decision making process. Obviously, the implementation of a smart system needs investment and this stakeholder perspective is inevitable.

This small analysis shows that the implementation of a smart system always involves multiple stakeholder perspectives. Note that which stakeholders are taken into account is case specific but it is evident that a selection of multiple stakeholders is necessary in order to find the value of a smart system.

2.3 Added value

The added value of a smart system can be defined in different ways. The research question implies that the added value is defined based on the preferences of the stakeholders. Preference and added value have similar but not identical definitions. Arkesteijn et al. (2017: p.244) describes added value and preference as following:

> *"We note that to decide is to choose. We choose the alternative that we prefer, and prefer the alternative that adds value. This means that value can be measured by measuring preference, that is, evaluating/judging the alternatives as to the value they add, and in this context, value and preference are equivalent".*

The decision-making process of the transformation of a building into a smart building is also the process of choosing the preferred option, the option that adds value. Based on the statement it is correct that the preference of stakeholders is used to determine the added value of a smart system.

Smart systems and its general added value

Kejriwal (2016), a smart technology expert at Deloitte, describes the general value of smart systems by naming three objectives in the Corporate Real Estate (CRE) theory: efficiency, differentiation and new revenue opportunities.

Efficiency is mostly researched with the aim to reduce energy, repair and maintenance and Real Estate costs. The continuous monitoring and predicting capability is a tool for building managers to take appropri¬ate corrective action which can result in lower asset risk and enhanced portfolio management capabilities (Kejriwal, 2016). For example, tracking the flow of people can be used to analyse occupant behaviour. It can then be used to better align space and activities based on this information.

The second objective described by Kejriwal is the opportunity to differenti¬ate by using the information to identify unmet consumer demands, provide more sophisticated services to their tenants and transform tenant and user experience (Kejriwal, 2016). It can support daily working activities of the users of the building. An example given by the Kejriwal is use of data about the movement of individuals through open spaces to help tenants boost the productivity of workers by better designing tasks and breaks to facilitate collaboration and even socializing between employees (Kejriwal, 2016). Secondly, it can give competitive advantage to the tenant and the owner. Both the tenant and the owner operate in a market with competition and changing patterns in consumption and work. This forces compa¬nies to revaluate their CRE space usage as they look for innovative ways to stay ahead of competition (Kejriwal, 2016). Smart systems are an intervention that gives them competitive advantage in the market. In other words, differentiate them from competition.

The last objective of a smart system described by Kejriwal (2016) is that of creating value through new revenue sources. Companies applying smart systems can perhaps offer analytics-as-a-service. The data present in the integrated platform and the analysed information could be sold to other interested parties. For example, the flow of people through a public building can be sold to advertisers or urban planners and building performance data can be used to support investors in their decision-making.

Indoor positioning and reference preferences

A step further into specific preferences for indoor positioning systems is the research of Mautz (2012). Mautz (2012) assessed the features of all technologies capable of indoor positioning and matched them with the user requirements. He states that it is a crucial element for any initiative to design an indoor positioning system is a thorough study of the user requirements and specific application descriptions in order to justify the research and development in this field. He developed a model of 16 general user requirements that illustrates the complexity and multi-dimensionality indoor positioning technologies (see figure 2.3) (Mautz, 2012). The requirements can be used to support specifying preferences. It can be used as another reference to define the criteria of the stakeholders.

Figure 2.3 User requirements for indoor positioning systems (Mautz, 2012).

2.4 Decision model

As decision-making processes are becoming increasingly complex, featuring high uncertainty and conflicting objectives, mathematical models are being developed that support this process (Razmak, 2015). A decision model can be defined as a system that aids a decision-maker in making a decision, by utilizing data through models that mathematically solve multi-criteria problems (Meijer, 2017).

Decision-making is the term generally associated with the problem solving process. Problem solving can be defined as the process of identifying a difference between the actual and the desired state of affairs and then taking action to resolve the difference (Anderson et al., 2016). Anderson (2016) identifies that decision-making is the first five steps of problem solving (see figure 2.4 left).

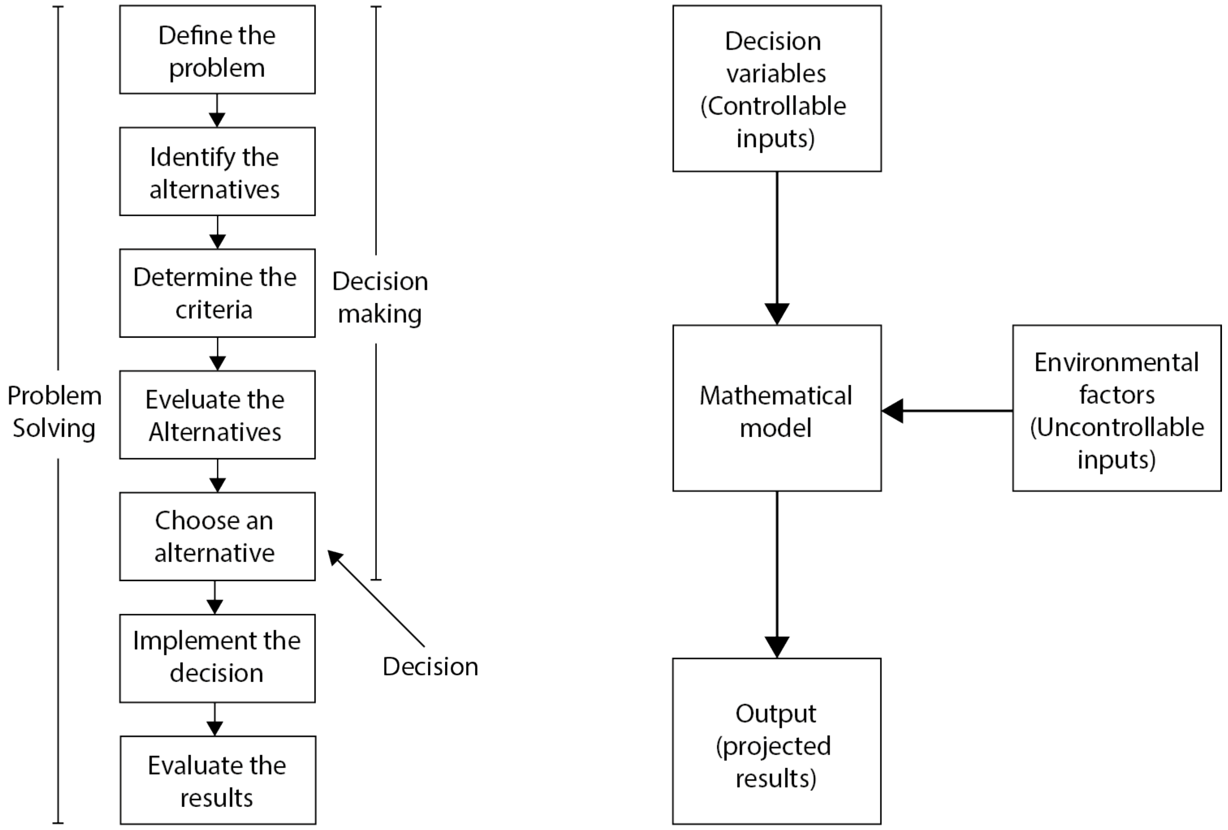


Figure 2.4 Problem solving and Decision making (Left) and flowchart of the process of transforming model inputs into output (right) (Anderson et al., 2016)

A decision process starts with the recognition that a problem exists (Meijer, 2017). Once the problem has been structured, the decision-making process may take two basic forms: qualitative and quantitative. Qualitative analysis is based primarily on the decision maker's judgment and experience (Anderson et. al, 2016). With the quantitative approach, the decision maker will concentrate on the quantitative facts or data associated with the problem and develop mathematical expressions that describe the objectives, constraints, and other relationships that exist in the problem.

In the field of science, mathematical models are a critical part of any quantitative approach to decision making (Anderson et al., 2016). The process of a mathematical model is transforming model inputs into output. The input consists of decision variables, which are controlled by the decision maker. Input that is not controlled by the decision maker are environmental factors. Once all input is specified, the objective function and constraints can be evaluated and the output of the model is determined. The output of the model is simply the projection of what would happen when those variables occur in a real situation (Anderson, et al. 2016).

Van der Voordt (2016) expressed that in the literature of added value, the operationalisations of parameters for a decision model is researched by making each value measurable and manageable, to explore which building characteristics and facilities may contribute to it and how a changing context may influence the most appropriate interventions. Especially measurability is critical because of qualitative values. The success of the mathematical model and quantitative approach will depend heavily on how accurately the variables can be expressed in terms of mathematical equations or relationships (Anderson et al., 2016). Secondly, the model should be capable of incorporating changing contexts, such as a changing economic environment. Appropriate methods exist for both challenges, the Lagrange curve and iteration, which will be explained in detail in the Research method paragraph. When all preferences can be made measurable, a decision-model is capable of giving the added value of each design alternative.

2.5 Rationality in decision-making

Meijer (2017) wrote his thesis about incorporating risk in the preference-based decision-making processes and Meijer (2017) and Arkesteijn et al. (2015) used the concept of rationality to answer the research question and organize their process accordingly. The following definition of rationality by Kickert (1980: p.60) is used to describe the decision making process:

"Rationality in decision-making behaviour is a concept that deals with behaviour. As behaviour is generally considered to be a choice made between alternatives, rationality is therefore a concept that deals with the way one chooses between alternatives."

The applicability of the decision model is to support choosing between alternatives and the decision-making process can be described using rationality. Meijer (2017) uses the three levels of rationality to develop a framework for his research process: substantive, procedural and structural rationality. The framework forms the basis of executing his research and is shown in figure 2.5.

The first rationality is procedure rationality. This is a list of all the steps that need to be taken to come to the desired outcome. It is the determination of the best procedure of decision-making by splitting the research in pieces and decide how the pieces have to be ordered (de Leeuw, 1992). The procedure explicitly explains what needs to be done to continue to the next step but does not explain how it can be done.

The second rationality is structural rationality. It describes the stakeholders that are involved and what they should do in order to come to a decision (de Leeuw, 1992). It describes the activities related to procedure. Each activity has as goal to complete one or multiple steps of the procedure.

The third rationality is substantive rationality. It describes the strategy and method for finding the answer (de Leeuw, 1992). In case of operational research, such as in the research of Meijer (2017), a tool is developed to find the answer.

Based on these three rationalities the execution of the research can be prepared. First, the research method will be chosen. This will be the description of substantive rationality. After the method is established, the procedure and structure can be developed. The procedure and structure can be combined to create a flowchart. Such a flowchart is made by Arkesteijn et al. (2017) (see figure 2.6). It shows the relationship between the stakeholders, steps, activities and the model building as well as the feedback loop (Arkesteijn et al., 2017). The flowchart provides a good overview of how the research was carried out or to visualize the predicted research process.

```
preference_score_high = []
value_high = []
for i in Criteria:
   print("For criterion", i, ",")
   item = input("Please enter the
   preference_score_low.append(i
   item = input("Please enter corr
   value_low.append(item)
   item = input("Please enter the
   preference_score_med.append
```

Figure 2.5 Framework for the decision-making process (Meijer, 2017).

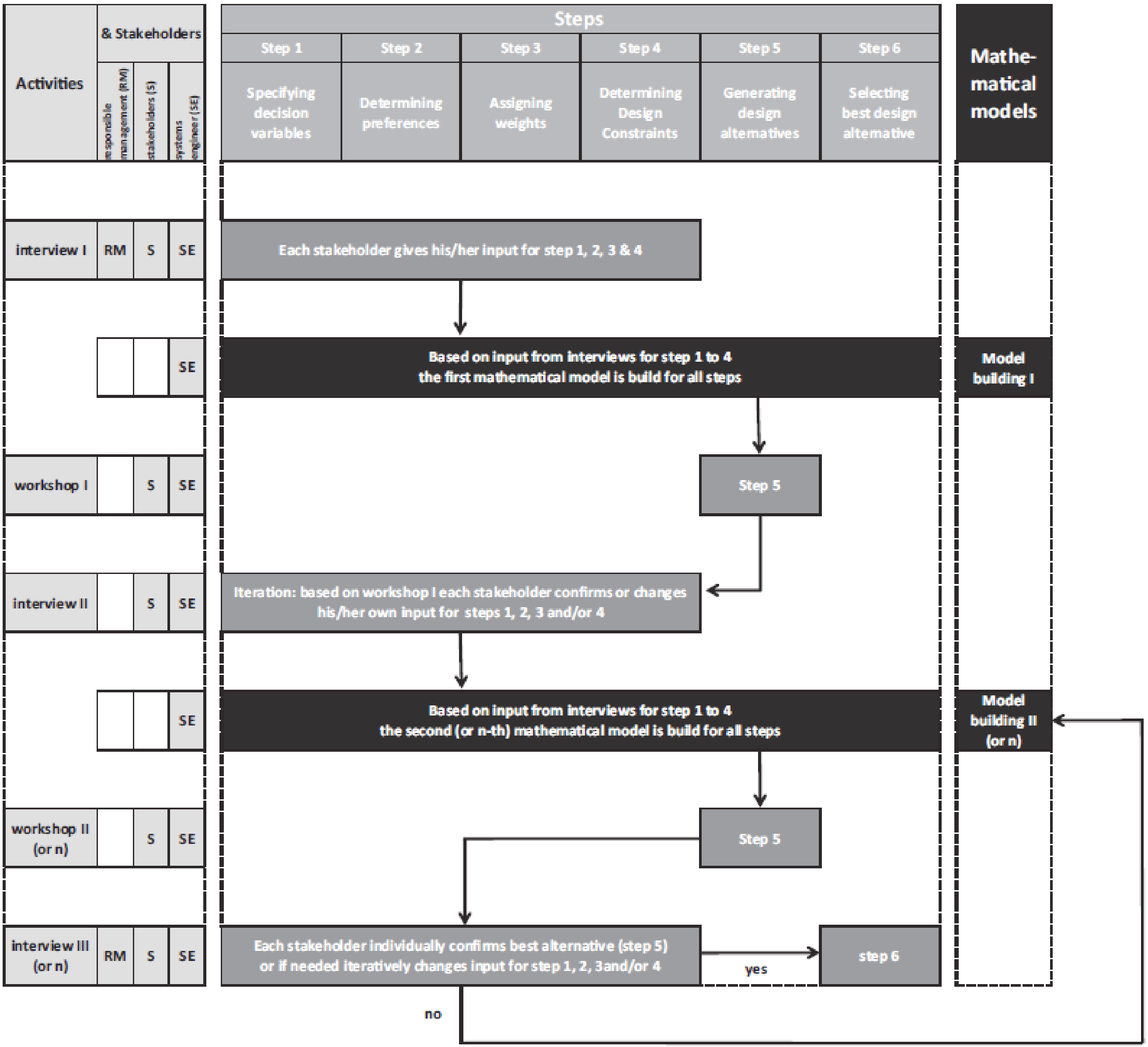


Figure 2.6. Flowchart of the preference-based accommodation strategy design approach (Arkesteijn et al., 2017)

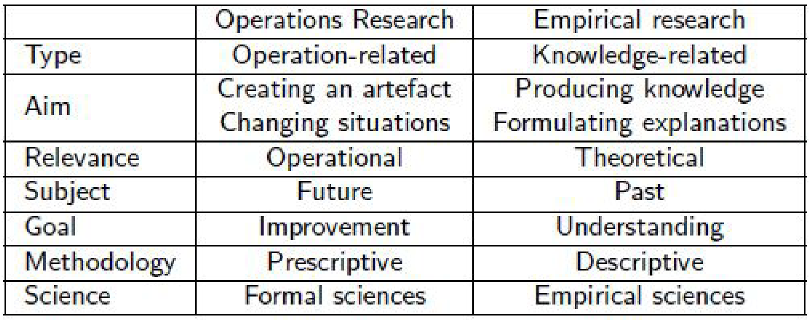
Chapter III Research Method

3. Research method

Establishing the research method was a process of comparison, each step going further into detail. This chapter will explain the process from a general research method to a specific method, including research techniques from other literature.

3.1 Research design

The main question describes a design problem and is aimed at making operation related solutions towards the future. As discussed in the problem statement there is a distinction between empirical and operational research (see figure 3.1). The problem statement and research question imply that this thesis is future oriented, aimed to improve by creating an artefact and changing a situation. Therefor an appropriate research methodology is that of operational research.



	Operations Research	Empirical research
Type	Operation-related	Knowledge-related
Aim	Creating an artefact Changing situations	Producing knowledge Formulating explanations
Relevance	Operational	Theoretical
Subject	Future	Past
Goal	Improvement	Understanding
Methodology	Prescriptive	Descriptive
Science	Formal sciences	Empirical sciences

Figure 3.1 Distinctions between operational and empirical research (Binnekamp, 2014: p.1).

The development of an artefact (decision model) to solve a problem is considered a design process (Binnekamp, 2014). Dym and Little (2004) visualize the operational design process as a step-by-step plan (see figure 3.2: left). However, the process is in fact cyclical in nature (Binnekamp, 2014). The steps to model, analyse, test, evaluate, refine and optimize the design are an iterative process in which the input and design are improved until a satisfied design is achieved (see figure 3.2: right).

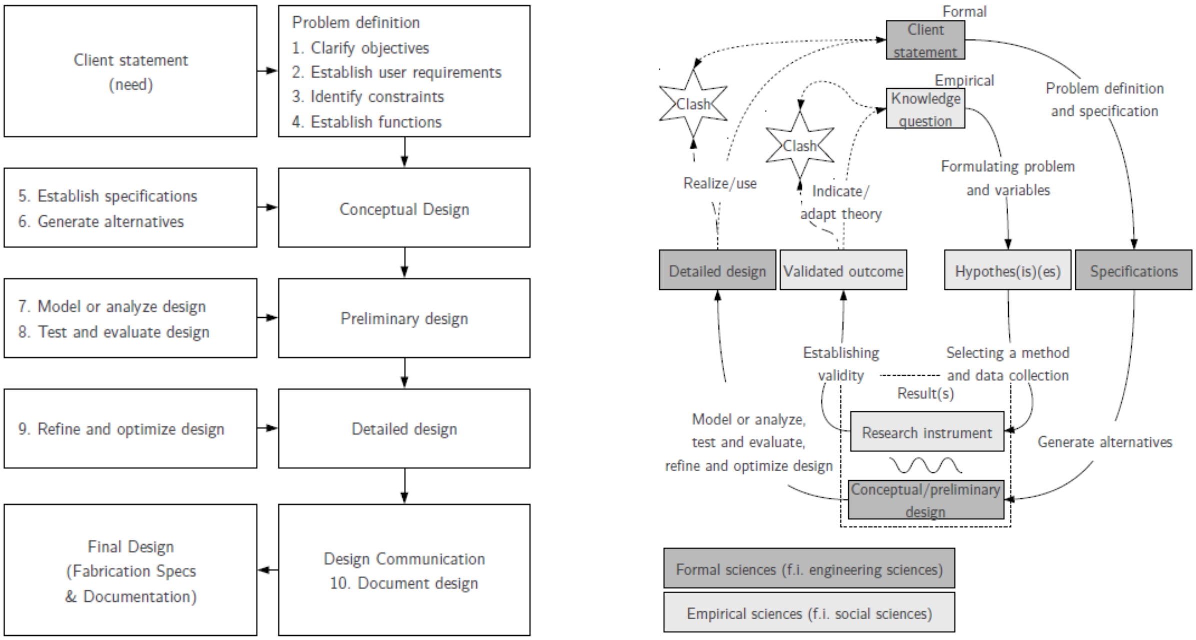
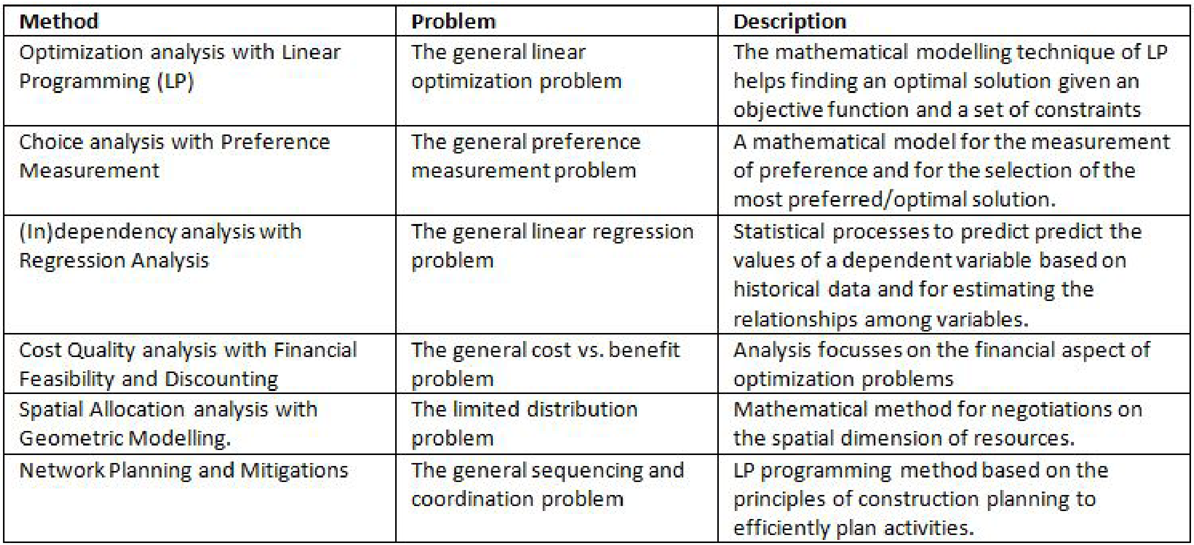


Figure 3.2. Left: Steps of a design process (Dym & Little, 2004).
Right: the formal and empirical research cycle combined (Barendse et al., 2012).

In the figure of Barendse et al. (2012) empirical research is also part of the cycle. The empirical cycle comprises of the identification of data input for the model. Empirical research is useful to define the input as it consults knowledge and literature. Operational research and its methodology are the directory of the research with empirical research providing the input.

3.2 Operational research

Operations Research, nowadays also called Management Science, is a discipline dealing with the application of analytical methods to aid decision-making and solve design problems (Arkesteijn et al., 2017). In the built environment, a small set of problem types have been identified which account of most of the problems. Because of the frequent reoccurrence of certain problems, several standard analytical methods do already exist (Binnekamp, 2014). In the table below, I summarized the description by Binnekamp (2014) of common applications in the field of operational research:



Method	Problem	Description
Optimization analysis with Linear Programming (LP)	The general linear optimization problem	The mathematical modelling technique of LP helps finding an optimal solution given an objective function and a set of constraints
Choice analysis with Preference Measurement	The general preference measurement problem	A mathematical model for the measurement of preference and for the selection of the most preferred/optimal solution.
(In)dependency analysis with Regression Analysis	The general linear regression problem	Statistical processes to predict predict the values of a dependent variable based on historical data and for estimating the relationships among variables.
Cost Quality analysis with Financial Feasibility and Discounting	The general cost vs. benefit problem	Analysis focusses on the financial aspect of optimization problems
Spatial Allocation analysis with Geometric Modelling.	The limited distribution problem	Mathematical method for negotiations on the spatial dimension of resources.
Network Planning and Mitigations	The general sequencing and coordination problem	LP programming method based on the principles of construction planning to efficiently plan activities.

Figure 3.3 Operational research methods (Binnekamp, 2014)

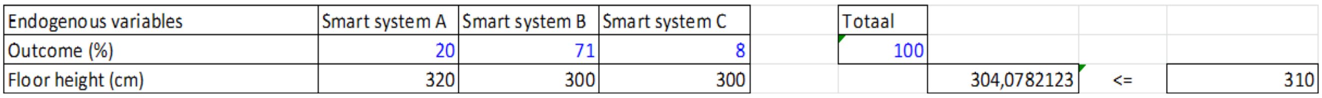
The description indicates that Optimization Analysis and Preference Measurement have common ground with the research problem and question. With Optimization Analysis it is possible to optimize the implementation of design alternatives in a building if the input is based on constraints and a single objective function. When an optimal solution has to be chosen based on multiple preferences and weights, Preference Measurement is most suitable. Regression analysis is not applicable as it seeks to find an average and not an optimum. Cost Quality Analysis, Spatial Allocation Analysis and Network Planning and Mitigations focus on other interests in the built environment and are not applicable for this thesis.

3.3 Study of Optimization Analysis and Preference Measurement

Delft University of Technology offers for both Optimization Analysis and Preference Measurement a computer program: Excel What's Best and Tetra Single Decision Maker (SDM). Both computer programs are explained and tested in order to find out which method is most useful for my research.

A convenient way of creating models to solve linear programming problems is to use the What's Best add-in for Microsoft Excel (Binnekamp, 2014). It is an excel format which leaves you free to predefine the amount of design alternatives and constraints. It gives an optimal objective function by either maximizing or minimizing. When performing an investigative study, by creating a fictional case, I encounter a couple of problems with the What's Best Model. The design alternatives are interdependent and the optimum outcome is the accumulative of all alternatives. In order to comply with the constraints, the alternatives average each other out. This is illustrated in figure 3.4

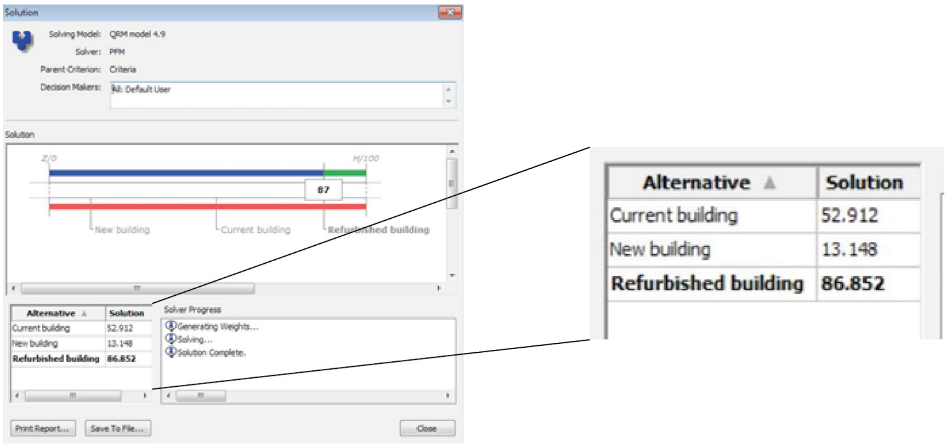
The floor height of the office is 310 cm and each of the smart systems needs a certain height in order to work efficiently. Smart system A needs 320 cm and system B and C need 300 cm. Smart system A would be impossible to install but due to the interdependent character it seeks an average between the three systems and gives smart system A score of 20. Secondly, not all preferences may be of equal importance and weights may need to be attached to the preferences. This is not possible in What's Best. Therefor the model does not have the intended purpose for this research.



Endogenous variables	Smart system A	Smart system B	Smart system C		Totaal			
Outcome (%)	20	71	8		100			
Floor height (cm)	320	300	300			304,0782123	<=	310

Figure 3.4. Excel What's Best outcome

The second decision model is based on the theory of Preference Measurement. The main results of this theory are the construction of measurement scales to which linear algebra and calculus are applicable (Binnekamp, 2014). A Preference Function Modelling (PFM) software tool that is capable of solving linear programming problems is Tetra SDM. The Tetra model is making a comparative assessment of the design alternatives considering the users (or users') criteria weights and alternatives' ratings. The solution is a score between 100 (maximum) and 0 (minimum). The highest score, in this case 87, is the best option and the closer to 100 the more it suits with the preferences of the stakeholders (see figure 3.5). Based on the investigative study, the Tetra model, or more general speaking: Preference Measurement, is suitable for my research.



Solving Model: QRM model 4.9
Solver: PFM
Parent Criterion: Criteria
Decision Makers: All: Default User

Alternative	Solution
Current building	52.912
New building	13.148
Refurbished building	**86.852**

Solver Progress
Generating Weights...
Solving...
Solution Complete.

Figure 3.5.Tetra outcome

3.4 Preference measurement

Barzilia (2005) has developed the theory of (preference) measurement. The main results of this new theory are the construction of measurement scales to which linear algebra and calculus are applicable. The reason of the development of this model is that preference, or value, or utility, is not a physical property of the objects being valued. Preference is subjective or personal by its very nature in the sense that when preference is measured, the system under measurement includes a person or persons (Barzilia, 2005). It is those persons that scale their preferences in order to get a mathematical representation of the reality. This means that the operation of preference measurement will result in scales, which are unique (Barzilia, 2010).

Within preference measurement, two research methods are particularly interesting for this research: Preference Function modelling (PFM) and Preference Based Design (PBD). First, the difference between PFM and PBD will be explained, an existing approach of each method is presented and the most suitable method will be selected.

Preference Function Modelling (PFM) vs. Preference Based Design (PBD)

Within Preference Management theory there is a subtle difference between two types of research: Preference Function Modelling (PFM) and Preference Based Design (PBD). PFM is an evaluation methodology, helping decision makers to choose the most preferred design alternative from a set of predefined alternatives. PBD is a design methodology, used to generate design alternatives based on preferences and weights. PBD is used when the design alternatives are not know a priori (Binnekamp, 2010).

PFM

PFM offers a correct model for the measurement of preference and for the selection of the most preferred solution. PFM is an evaluation methodology, helping decision makers to choose the most preferred design alternative from a set of already existing alternatives (Binnekamp, 2010). Binnekamp (2010) concluded in his research that PFM is the only decision theoretical methodology that enables the construction of measurement scales to which linear algebra and calculus are applicable.

Based on this theory the software tool Tetra is programmed. The process of using Tetra to make a decision consists of six steps (Binnekamp, 2014):

1. Define the decision makers who will be involved in the process
2. Define the alternatives to be considered in making the decision.
3. Define the criteria upon which the decision will be based. These criteria may be defined in a tree like structure, using main criteria, sub-criteria, sub-sub-criteria and so on.
4. Define the weights for all the criteria. These are defined relatively, specifying how important each criterion is in relation to others. The weights are defined in each node of the criteria tree.
5. The decision makers enter their ratings for each alternative with respect to each criterion.
6. Solve the model that has been created by the previous steps to compute the overall scores and get a numerical rating of the alternatives that corresponds to the combined ratings of all of the decision makers.

Anderson (2016) also described a step by step approach to identify the best decision alternative for a multi-criteria decision problem. The scoring model can assist in analysing a multi-criteria problem and help identify the preferred decision alternative. The step-by-step approach of Anderson (2016):

1. Develop a list of the criteria to be considered. The criteria are the factors that the decision maker considers relevant for evaluating each alternative
2. Assign a weight to each criterion that describes the relative importance.
3. Assign a rating for each criterion that shows how well each decision alternative satisfies the criterion.
4. Compute the score for each alternative
5. Order the alternatives from the highest to the lowest score. The alternative with the highest score is the recommended decision.

Van Alphen (2016), a graduation student of the Delft University of Technology, also used the PFM methodology. The aim of their research was to establish the most suitable dwelling for home seekers. By using the PFM and a decision model, she was able to support the decision-making of finding the optimal home. Van Alpen (2016) encountered difficult variables such as aesthetics. To solve the problem she limited the amount of options and constructed a series of images or illustrations for each variable. The decision-maker was asked to choose the most and least preferred option and rate them respectively 100 and 0. Subsequently the decision-maker had to rate all other options between 0 and 100. This resulted in a preference scale, which could be used to establish the preferences of the design alternatives.

PBD

This new theory of preference measurement has been developed by Binnekamp (2010). The reason behind this theory is defined as follows:

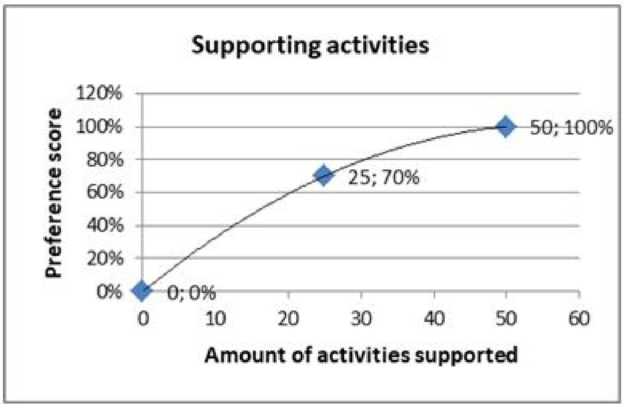
> *"In the domain of architecture we face the problem that a multitude of design alternatives can fit an intended purpose. It would be too time-consuming to ask an architect to make drawings of every conceivable design that fits an intended purpose and then analyse them by enumeration using PFM. What we need, therefore, is a design methodology where the alternatives to be evaluated are not known a priori" (Binnekamp, 2010. P. 54).*

The design methodology proposed by Binnekamp (2010) focusses on design in which (1) the number of potential designs is very large, perhaps even infinite, or (2) the number of design variables is large, as is the number of values they can assume (Dym & Little, 2004). In other words, in this case it is impossible to present and evaluate each design alternative.

PAS approach by Arkesteijn et al. (2017)

A research were this methodology is applied is the Preference-based Accommodation Strategy (PAS) by Arkesteijn et al. (2017). The PAS approach is a design procedure that enables CRE managers to design a real estate portfolio, makes use of scales for direct measurement of added value/preference, and allows the aggregation of individual ratings into an overall performance rating. Their methodology is an iterative process in which the model could be adjusted in accordance with the results of the evaluation of intermediate solutions. The PAS model is created as an add-on for existing CRE alignment models and the approach of PAS is generic and can be used for a wide range of problems in real estate portfolios (Arkesteijn, et al., 2017). The research is a design process in which the alternatives are not known a priori. With the use of a mathematical model, the decision-makers are able to design an optimum design alternative based on their preferences.

Arkesteijn et al., (2017) uses the Lagrange curve to scale the preference of a variable with an undefined number of options. For example, the preferred distance of a food facility. Distance gives an unlimited amount of options and the Lagrange curve can be used to find the preference for each distance. The Lagrange curve is a polynomial $P(x)$ of degree $\leq (n = 1)$ that passes through n points $[x1, y1 = f(x1)]$, $[x2, y2 = f(x2)]$, $[xn, yn = f(xn)]$ (Arkesteijn et al., 2015). In other words, the curved line goes through three points predefined by the decision-maker. This is done by letting the decision maker determine a bottom reference, top reference and intermediate reference. The X-axis is the value and the Y-axis is the preference score rating from 0 to 100. For each value of X, the preference score can be found on the curve. The figure below illustrates an example of the Lagrange curve.



The X-axis is the amount of activities that are supported by the smart system. The bottom reference, zero activities supported is determined by the decision-maker with a preference of 0. The maximum amount of preferred activities supported is 50 and therefor rated with 100 (top reference). The intermediate reference set on 25 activities is rated by the decision-maker with 70. This gives the model a curve on which each smart system can be rated. If for example a smart system supports 20 activities the preference score is approximately 60.

The preference score can be calculated using the following formula:

$$P(x) = ((x - x1)(x - x2)/(x0 - x1)(x0 - x2)) * y0 + ((x - x0)(x - x2)/(x1 - x0)(x1 - x2)) * y1 + ((x - x0)(x - x1)/(x2 - x0)(x2 - x1)) * y2\ldots$$

The problem of not knowing the alternatives in advance is solved by introducing synthetic alternatives. A synthetic alternative is an alternative associated with a value for a single decision variable value, regardless of other decision variables and regardless of its feasibility (Binnekamp, 2010). An example of a synthetic alternative is 'number of closed workspaces'. The preference of the design of one, two or any other amount of closed workspaces can be found on the Lagrange curve. With this method it is possible to not have design alternatives beforehand.

3.5 Research method: PFM

During the development of the research both PFM and PBD were considered and evaluated. Multiple smart systems fit the intended purpose. However, the amount of alternatives that fit the intended purpose is limited. It is possible to analyse them by enumeration. Moreover, designing the alternatives would presumably lead to an alternative, which is not available in the smart system market. Based on these finding during the development of the research it is decided upon to use the PFM methodology. The model will be used to evaluate alternatives and not to design an optimum alternative.

However, the research of Arkesteijn et al. (2017) provided a valuable 'lesson learned'. The lesson learned from the PAS approach is the iteration process. In workshops, the participants were asked to design the alternatives. This also gave them a better understanding of the model and their preference given earlier. After the workshop the participants were able to alter their input. Iteration made it possible for them to formulate the variables as they intended and improve the model (Arkesteijn et al., 2017). It was perceived as positive by both the researcher and the participants and should be included in this research. Anderson (2016) agrees with the process of iteration, as he states in his book about quantitative approach to decision-making, that by comparing the scores for each criterion the stakeholders can learn why a particular alternative has the highest score.

Secondly, the Lagrange curve could be a more efficient tool than the rating method from PFM. With quantitative values, such as costs, there is an undefined number of quantities. Whenever such a value occurs, the Lagrange curve can be used. The efficiency of this method is the flexibility. When the costs of a system changes there is no need to rerate the system. The new preference score can immediately be found on the curve. Secondly, when a new alternative is added, the preference score can also be found immediately. Third, it is assumed that the Lagrange curve may be an easier process for the participant. Rating the preference of irregular quantities may be difficult to do correctly and may lead to insufficient preference scores. Based on these assumptions, the Lagrange curve is taken into account as a secondary research technique.

3.6 Developing the decision model

The decision making process is based on the PFM methodology including the PAS approach and the seven steps of Tetra (Arkesteijn et al., 2017 and Binnekamp, 2014). The PFM methodology is elaborated using the three levels of rationality (Based on the PAS approach of Arkesteijn et al., 2017). The procedure consists of a step-by-step plan, consisting of nine steps. The structure consists of activities, divided into activities with the stakeholder and activities of the researcher. The information gathered forms the input for the mathematical model.

3.6.1 Workflow (procedure)

1. Select stakeholders. Each decision-making process consists of one or multiple stakeholders that are interested in the decision. All interested stakeholders need to be defined (Binnekamp, 2012).
2. Define variables. Each stakeholder specifies the decision variables he/she is interested in (Binnekamp, 2012).
3. Define constraints and criteria. The variables can be distinguished into constraints and criteria. The constraints are the feasibility restrictions with regard to maximum and minimum values to which the alternative needs to comply. Criteria are the preference of the stakeholder with regard to the alternatives

(Binnekamp, 2012). A variable can also be both.

4. Define weights. Each stakeholder assigns a weight to the criteria he/she is interested in, indicating the importance of the criterion relative to others (Binnekamp, 2012).

5. Define alternatives. Based on the constraints, alternatives can be selected. The design alternatives form the supply side of the research (Binnekamp, 2012).

6. Rate each alternative per criterion. Each stakeholder rates each alternative per criterion he/she is interested in. The rating must be executed with a top (e.g. 100) and bottom (e.g. 0) preference. A reference or alternative may be used to define the top or bottom preference (Binnekamp, 2012). This is necessary because for the model to work there needs to be an absolute minimum and maximum. If a criterion has an infinite unit, such as costs, the Lagrange curve can be also used (Arkesteijn et al., 2015). This is particularly useful when the variable is subject to change.

7. Rank list of alternatives. All design alternatives fit the intended purpose so in order to find the best alternative each alternative gets an overall preference score based on the preference rating and weight (Binnekamp, 2012). This is calculated by the model. The output of the model is a list ranking from the highest to the lowest overall preference score. The highest score is the best alternative.

8. Combine alternatives. Additionally it is possible to design a new (fictional) alternative. The new solution is the combination of features from different alternatives that received the highest score for each criterion. This can be done by the researcher.

9. Iteration. Arkesteijn et al. (2015) concluded their research with the fact that is was generally found difficult to express preferences into quantitative values. They derived to the solution of using an iterative process to adjust and improve the variables based on new insights or new information.

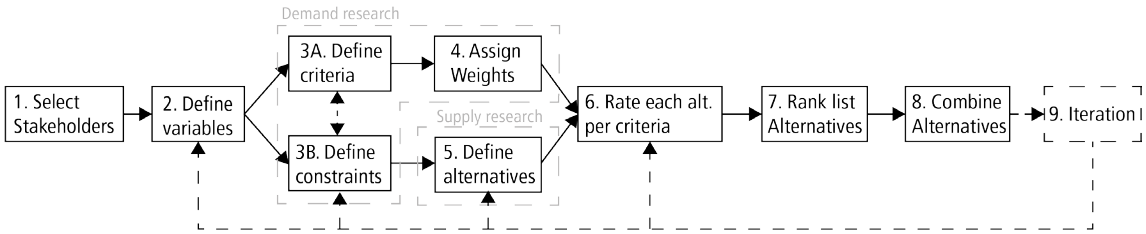


Figure 3.6.Procedure

3.6.2 Activities (structure)

In order to establish all steps described above a series of activities is needed. The activities consists of establishing the input for the model, which is done by the stakeholder, and the selection of the alternatives and development of the model, which is done by the researcher. Both are a cyclic process as described in the research design. The activities describe what should be done to complete the steps described above.

- Interview 1: acquaintance. the purpose of this interview is to get acquainted with all roles from the ownership and tenant side. In the interview, the purpose of the research will be explained. Secondly, the interviewee is asked what their role is and if significant interest regarding the research exists. This set of interviews supports the selection of the stakeholders.

- Interview 2: variables. the purpose of this interview is to define the variables the stakeholder is interested in and secondly to establish if the variable is a constraint or criteria. The variables will be established using an unstructured interview. However, the interview does have a plan of approach. The plan of approach is to discuss the problems and goals the stakeholder faces in its role. The problem or goal stated needs to be specified into a specific and unambiguous variable. Predefined follow-up questions such as; why is this important, what do you want to solve and who is involved help to further clarify the variables.

- Design alternative information. Based on the constraints, a list of feasible alternatives is selected (see 6.3 feasibility). Relevant information about each alternative must be documented. The information is gathered from the suppliers and experts. The document will be send to the stakeholders in order to prepare for the next interview.
- Interview 3: rating. The purpose of this interview is to ask the stakeholder to rate each alternative per criterion. This is done verbally and the model is filled in by the researcher. Relevant information is provided beforehand and made available in the Excel document. The stakeholder is able to discuss and ask questions during the interview.
- Model: Complete model. Before the start of the interviews, a blank model already exists. The algorithm is pre-entered and could easily be copied. During the interviews, each set of input is placed in its appropriate place. The completion of the model consists of an overview of all criteria, weight, alternatives and their preference scores. The output is the reference score for each stakeholder and the overall preference score. A list ranking from highest to lowest overall preference score can be made.
- Model: Combine. Each feature that scores highest on a certain criterion can be selected. When this is done for each criterion, a combination of alternatives is used to design a new (fictional) alternative. This could provide insight in what would ideally be achieved when designing a smart system for the building.
- Interview 4: Iteration. New insights during the process, comparing information and presenting the model and its output could initiate the stakeholders to adapt and improve the variables. Iteration makes it possible for the stakeholders to formulate the variables as they intended (Arkesteijn et al., 2017). By asking if there is any motive to adapt variables, the stakeholders are able to revise their input.

By combining the procedure with the structure a flowchart can be created (see figure 3.7). It shows the relationship between the different activities and which steps are to be completed in that activity. Some steps may be completed in another or additional activity.

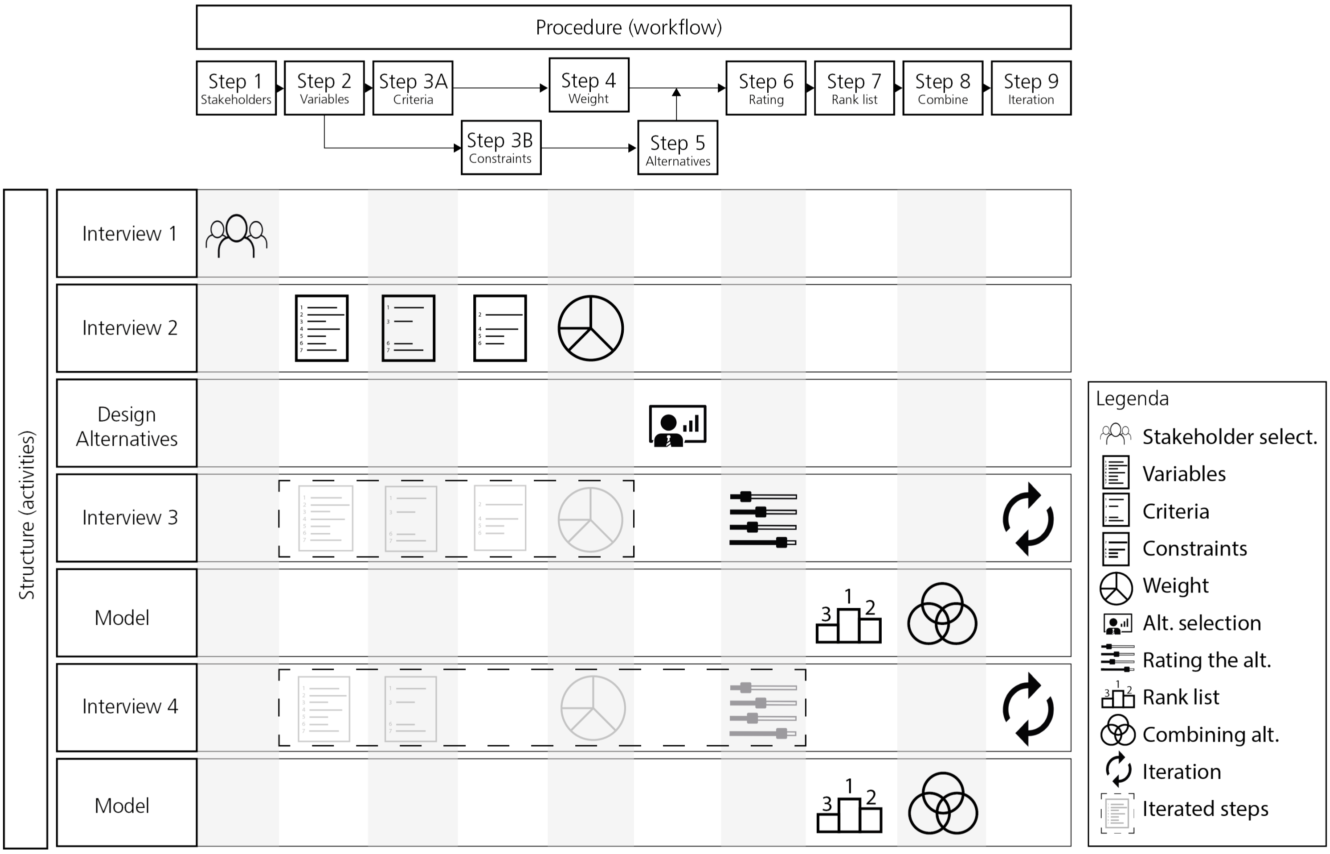


Figure 3.7 Flowchart (based on the PAS approach of Arkesteijn et al., 2017)

3.6.3 Feasibility

The data generated from the first six steps of the procedure serve as input for the model. This data is collected by interviews and produces four input data sets: constraints, preference scores, criteria weight and stakeholder weight. A constraint is a fixed requirement which cannot be violated in a given problem formulation. Constraints divide all possible solutions (combinations of variables) into two groups: feasible and infeasible. The constrains represent a maximum or minimum value. Before the preference scores, criteria weight and stakeholder weight can be put in the model the feasible alternatives need to be selected (Binnekamp, 2010). Based on the constraints the alternatives are evaluated by a group professionals and divided into feasible an infeasible. The feasible alternatives are selected to be implemented in the model. Binnekamp (2010) made a visual representation of such a feasibility selection (see figure 3.8)

The green dots are the feasible alternatives and the red dots the infeasible. The marked area is the field in which all feasible alternatives lie.

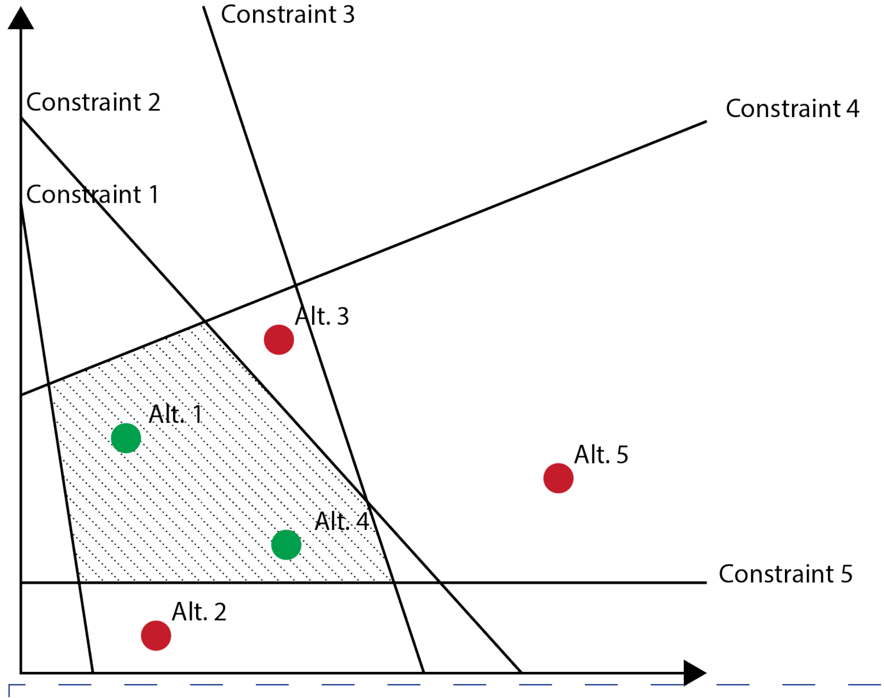


Figure 3.8. Visual representation of feasibility selection (based on Binnekamp, 2010)

3.6.4 Principal structure of the model

The preference score, criteria weight and stakeholder weight are the three numeric value sets as input for the decision model. The calculation of the overall preference score consists of a couple of formulas. The first formula is to calculate the weighted preference score:

Preference score x criterion weight = weighted preference score

For the research it is relevant that the preference score of each stakeholder is established so he/she can see which alternative fits their preference and why. The second formula is to calculate the overall preference score for each stakeholder:

Weighted preference score 1 + weighted preference score 2 + …. = overall stakeholder preference score. For example 6 criteria in excel: =sum(weighted preference score 1: weighted preference score 6).

The decision maker also assigns a weight to each stakeholder. The next step is to calculate the weighted overall stakeholder preference score.

Overall stakeholder preference score x stakeholder weight = weighted overall stakeholder preference score.

The last step is to calculate the overall preference score by sum up all weighted overall stakeholder preference scores:

Weighted overall stakeholder preference score 1 + Weighted overall stakeholder preference score 2 + … = overall preference score.

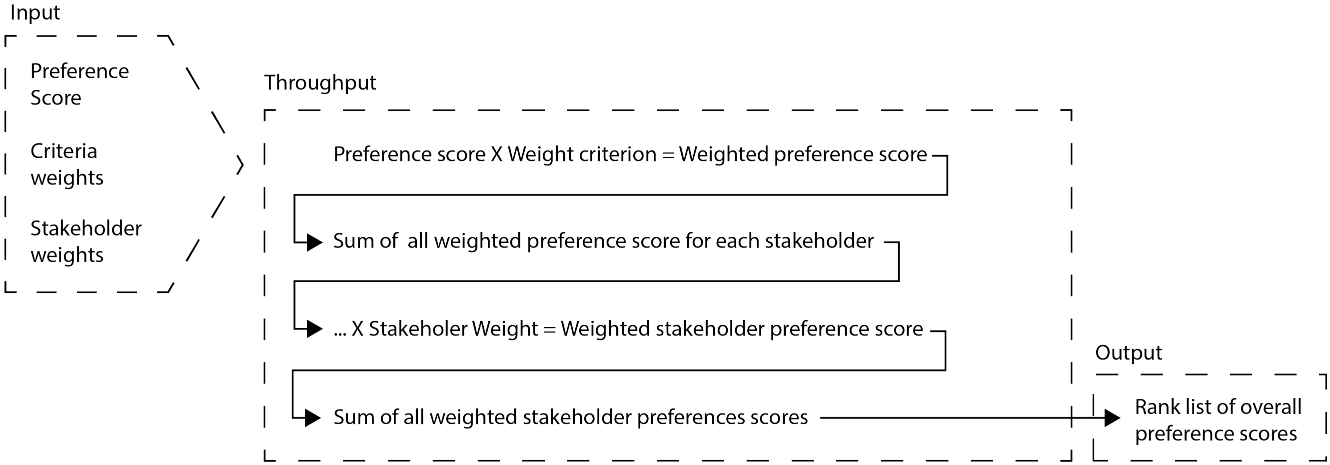


Figure 3.9. Principal structure of the model

Additionally it is possible to calculate the weighted gap between the preference score and highest preference score, 100 in this case. The weighted gap is the amount that can be added up to the overall stakeholder preference score if the criterion would be 100. In other words, it is the maximum increase in overall stakeholder preference score. When the number is high there is still a lot of potential to achieve better on that criterion. If the score is low most of the possible score is achieved. The formula for the weighted gap is:

(max score – preference score criterion) x criterion weight = weighted gap (for the overall stakeholder preference score)

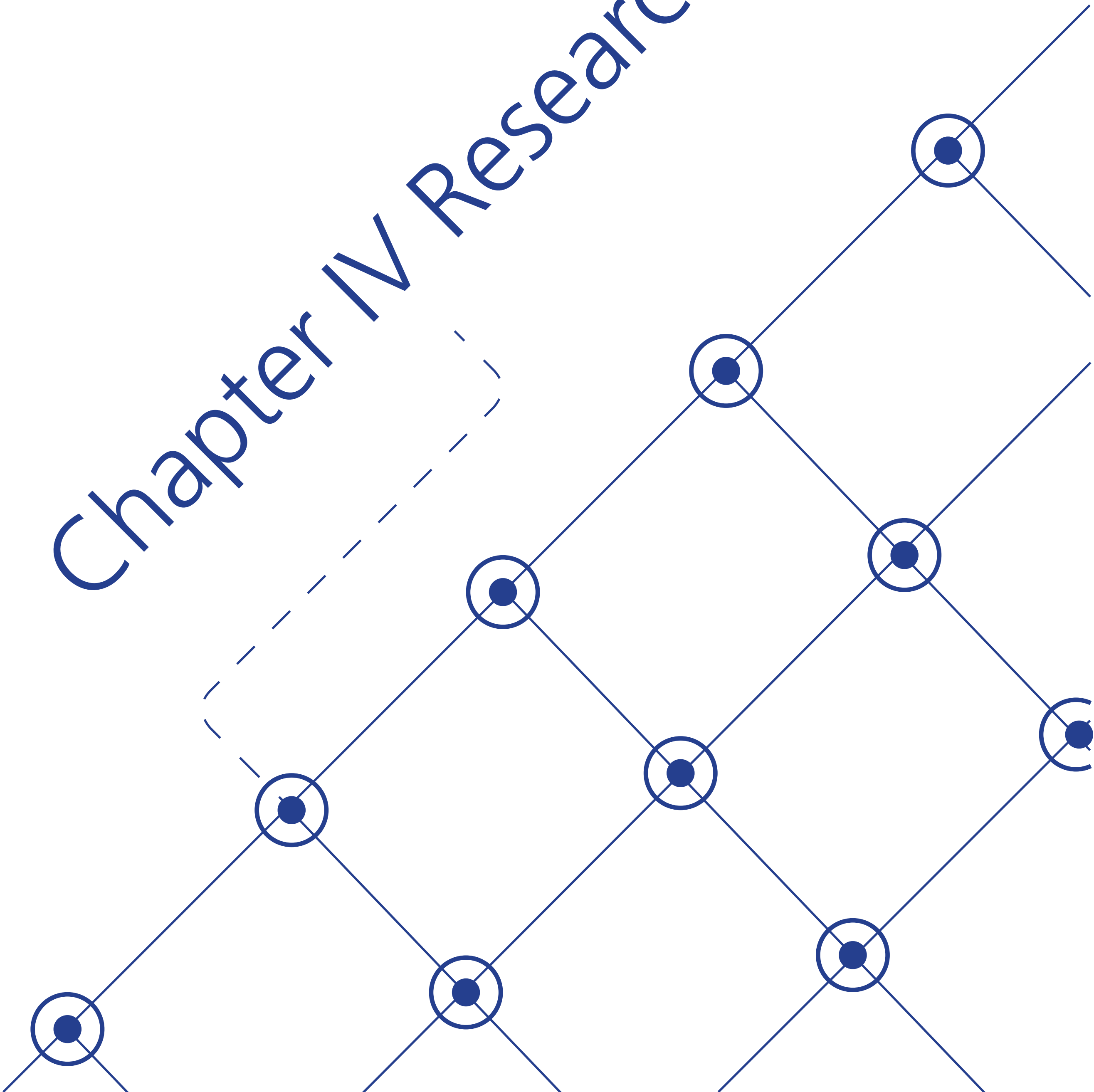
If you want to know what the maximum increase in score is for the overall preference score per criterion, the following formula can be used:

(max score – preference score criterion) x criterion weight x stakeholder weight = weighted gap (for overall preference score).

Step 8 of the workflow is the design of a combined alternative, which consists of all the features that get the highest score. To get this in a simple overview it can be done manually but it is more efficient if done automatically. The formula to automatically design the combined alternative is the IF function. The formula for each criterion is as follows:

IF(preference score Alternative 1 = max score; "Alternative 1"; IF(preference score Alternative 2 = max score; "Alternative 2"; IF(…

Chapter IV Research



4.1 Introduction of the case

In this chapter, the pilot study will be explained. In order to get an overall picture of the environment the case will be explained on four scales, from general to specific. Most general is Schiphol, the complete area managed by Schiphol Group. One scale smaller is the Schiphol Central Business District (CBD), which is managed by Schiphol Real Estate (SRE). Again one scale smaller is the Schiphol Office Building (SHG), which is the headquarter of Amsterdam Airport Schiphol. The smallest and most specific scale is the E-wing, the subject of my research. The decision that is going to be made is based on the implementation of smart systems in the E-wing.

4.1.1 Schiphol

Schiphol Group is an airport operator and owner of Amsterdam Airport Schiphol, Rotterdam The Hague Airport and Lelystad Airport. The most important airport is Amsterdam Airport Schiphol and this is where Schiphol Central Business District (CBD) is located. Schiphol is one of the largest airports in Europe and has a prime office centre with more than 500 companies and 65.000 employees working every day in the area. Schiphol is located in the municipality the Haarlemmermeer and the CBD is located next to the passenger hall. All the land is privately owned by Schiphol Group.

4.1.2 Schiphol Central Business District (CBD)

Schiphol Real Estate (SRE), a 100% subsidiary of Schiphol Group is responsible for the development, investment, maintenance and asset management of all the commercial properties in the Schiphol CBD. SRE owns in total 228.000 sq. of office and 313.000 sq. of operational real estate. The average rent is €229 sq./yr. which is significantly higher than the national average of €120 sq./yr. The real estate of Schiphol is mostly high-end.

SRE is constantly (re)developing commercial property in order to create and maintain an effective and attractive business location. Their property strategy is to develop and buy commercial real estate to maintain it for the long term. SRE does not desire to sell their property. They are owner of approximately 90% of the buildings at Schiphol and want to achieve to be 100% owner.

The vision of Schiphol Real Estate (SRE) is to create places where people and business want to be. The CBD should optimally support the business of our tenants and visitors. SRE has four focus points: Flex, Sustainable & Health, Connect and Smart (Ven, 2017).

- FLEX: SRE develops flexible real estate solutions that are able to adapt with the changing demands of the tenants.
- SUSTAINABLE & HEALTH: the existing stock is in the process of sustainable improvement. New developments are in line with the advanced sustainable requirements. The offices have an excellent indoor climate to support the health of the users and visitors.
- CONNECT: The CBD is an area where people can meet, interact and built a network. It is place where people and business can grow.
- SMART BUILDINGS: SRE digitalises the built environment in order to meet the demands of users and visitors. Smart is the over-arching concept for the other three focus points.

The smart building concept is the coherent focus point. It enables and supports the other three focus points. SRE recently stated that their vision is to transform Schiphol CBD into a smart area by integrating smart systems not only on building level but also on area level. Willem van der Ven (2017), area developer at SRE, elaborates on the envisioned roadmap of Schiphol. The smart building implementation has started with the Microsoft office building: The Outlook. Secondly, they want to expand by redeveloping other buildings into smart buildings. The third step is to connect buildings, public space and parking with each other. Currently they are at the second step, redeveloping buildings into smart buildings.

SRE expressed the importance to involve all interested stakeholders in the process of determining which interventions add the most value.

Figure 4.1 Central Business District (Engelhard, 2018)

4.1.3 Schiphol office building. Dutch: Schipholgebouw (SHG)

The next desired redevelopment is that of the Schiphol office building (SHG). The SHG is located at the end of the CBD and only accommodates Schiphol related companies. SHG is owned and managed by Schiphol Real Estate. The Useable Floor Space (UFC) of the complete SHG is 29.878,3 m2.

The state of the building is according to regulations. The building has an energy label A and the building envelope is technically and energetically in good state.

The SHG is owned by Schiphol Group, managed by Schiphol Real Estate and used by all divisions of Schiphol. An advantage of this building for the pilot study is that stakeholders and information are easy accessible. Stakeholders of other buildings in the portfolio have a higher threshold to be contacted for interviews. It is assumed that this enables a more smooth process.

Figure 4.2 Schipholgebouw (SHG) (Engelhard, 2018)

4.1.4 E-wing

The research focusses on the E-wing because this is the part of the building where smart systems will be implemented first as part of pilot studies.

The UFC of the E-wing is approximately 5280 m2 (17,6% of SHG). The 5280 m2 is divided equally over six floors, each floor consisting of 880m2. The E-wing is occupied by different tenants, all subsidiaries of Schiphol Group. The ground floor and first floor are occupied by the accountancy department. The second and third floor are occupied by the procurement office. Floor four and five are occupied by Schiphol Real Estate themselves.

The layout of the offices are designed to the needs of the department but have strong similarities.

Each office plan consist of seven elements: the open work space, the hallway, the formal workplaces, the informal workplaces, the formal meeting rooms, the informal meeting rooms and the wardrobe. The layout of a typical floor of the E-wing is shown below. The only exception is the open workspace, which may not be present on an office floor.

The office has a climate ceiling including all technical elements such as heating, cooling, ventilation, lighting, power and internet grid. In most of the walls of the office, power plugs and connection to the internet can be found. The closed rooms (formal workplaces, formal and informal meeting rooms) also have a temperature control device.

The façade of the E-wing consists of a glass façade at approximately 80 cm from the floor up until the 15 centimeter below the ceiling and stretches along the entire length of the wing. The glass façade consists of two types of windows. The first is double glass with on the inside blinds and another glass plate is placed on the inside of the frame. The second is tinted double glass window, which can be opened manually.

SRE sees opportunity to implement hardware (sensors, gateways and devices) in the ceiling, partition walls, windows, under the glass frames of the outer walls, and tables (workplaces and meeting rooms). It is not desired to implement hardware in the floor. The office also contains separate elements such as plantation, copy machines, basic kitchen (sink, fridge, drawers and coffee machine) and lockers. These elements are not primarily taken into account in the research.

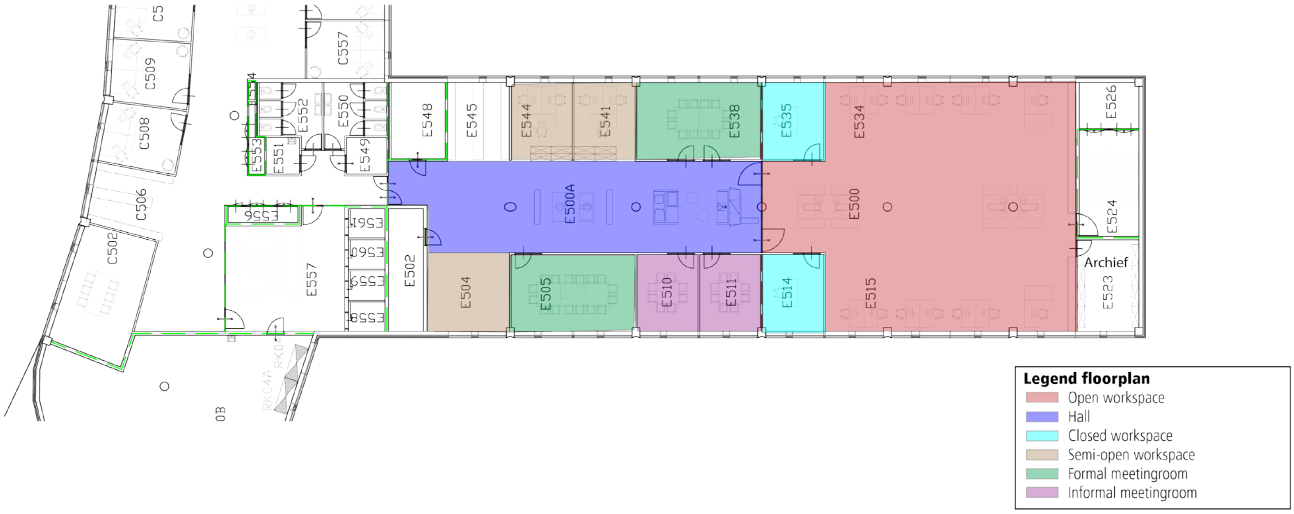


Figure 4.3. Floorplan of fifth floor of the E-wing

4.2 Results

In this chapter, the research will be explained in detail. The research will be explained using the flowchart (see figure 3.7: p.47). Within each step of the workflow, the activities to accomplish that step are explained.

4.2.1 Stakeholder selection

The SHG building is owned, managed and used by divisions of the Schiphol Group. The first interview is to analyze the building and get acquainted with the stakeholders. The interviews were indicated as an informal meeting and was unstructured. The goal of the interview is to establish the responsibility of the interviewee in order to establish their interest to the research. Secondly, the interview was used to briefly explain the research. 14 different roles were selected to be interviewed. The selection of roles were mainly management functions across the entire Schiphol Real Estate department including the tenant. Based on their responsibility and interest in the research eight stakeholders was selected.

The stakeholders consist of an area developer, investor, sustainability developer, property manager, technical property manager, maintenance contractor, tenant manager and the users. The roles of the stakeholders can be divided into two sides. The area developer, sustainability developer, investor, property manager and technical property manager (including maintenance manager) are the ownership side. The tenant manager and users are the tenant side.

The investor is responsible for the investment and ownership of all the commercial properties in the portfolio of Schiphol. One of these buildings is SHG. Schiphol Real Estate is invested for 80% in the SHG. The rest is invested by an external investor. The investor represents both investing parties.

Schiphol Real Estate has a number of developers responsible for the (re)development of commercial property. One of these developers is interested in the redevelopment of the CBD. His responsibility is that the redevelopment of each building is in line with the vision of the area (Schiphol CBD). The vision is to redevelop Schiphol CBD in Smart Airport City, a smart area.

The sustainability advisor is responsible for the sustainability goals that Schiphol Group has stated. Schiphol area should be zero waste by 2030, climate neutral by 2040 and should strive to be a healthy place for work and living. All assets of Schiphol, including the SHG should support these goals.

The property manager is responsible for everything that concerns the SHG directly. The property manager takes care of the financials, tenant relationship, supervising maintenance, construction works and manages regulations. Currently the main objective is the redevelopment into a smart Building. He is directly responsible for the design, planning and implementation of the smart system.

The technical property manager is responsible for the installations in the building such as the HVAC system, lighting and the Thermal energy storage System (Warmte Koude opslag, WKO). This team takes care of the planning on daily, yearly and a multi-year plan to maintain the installations in the building. The most important installations are the climate ceiling, lightning and toilettes.

The maintenance contractor is appointed by the technical property manager to carry out the planning. The maintenance contractor is an external party (Engie) and is contracted 1 February 2018 for 5 years. The technical property manager and maintenance contractor work closely together and it is decided upon to combine both as one stakeholder.

The tenant managers are responsible for the accommodation and contracting of the tenants. The layout and daily work routines of the users are planned and controlled by the tenant managers. There main objective is to align accommodation and company as well as possible. They are in very close contact with all the users of the SHG and valuates the objectives of tenants. However, the tenant managers also has their own agenda, which may differ from the users.

ca.200

The users are the people accommodating the E-wing. The E-wing approximately accommodates 200 people. Any technological intervention should support the users and especially smart systems could place great emphasis on the user of the building (Arditi, 2015). The users of the building will use and experience the smart systems along with their daily work routine. The criteria of users are therefor of great importance. It is not feasible to establish the criteria of each user. Therefor a panel will be established that will represent the user perspective. In order to create a representable panel, five managers of the different departments are selected. It is assumed that they know best what the variables, weight and preference of their staff is.

4.2.2 Specify variables

Each stakeholder has a specific role. From their role the stakeholders express interest in the implementation of a smart system in the SHG building. The variables the stakeholders are interested in are established using a semi-unstructured interview. The interview is not bound to an order of questions but does have a plan of approach. The plan of approach is to discuss the problems the stakeholder faces in its role. Secondly, the goals of the stakeholder is questioned. The problems and goals can contain multiple variables. In order to define the variables, it is important to discuss their problems and goals until the variables are satisfied. It is the stakeholder that indicates if the variables are well defined and complete. During the interview the variables are discussed and shaped until the stakeholder states to be satisfied.

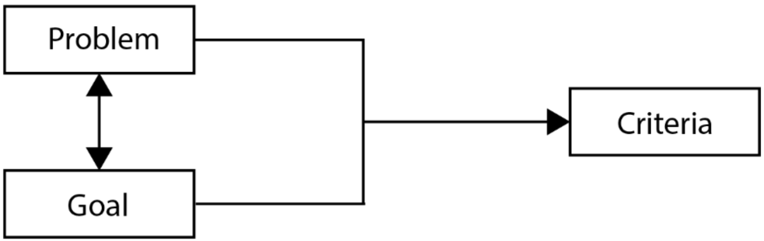


Figure 4.4 Approach second interview

At first, the seven stakeholders specified in total 47 decision variables (see chapter iteration, figure: p.65). When comparing the variables between stakeholders it is evident that there is a difference in how specific the variables are. Some stakeholders could very well express their variables while others remained more generic. For example, the difference between 'insight in building occupancy' and 'improve management'.

47 variables were established. 20 out of 47 variables are quantitative and the remaining 27 are qualitative. The possibility to include qualitative variables is therefore very important. An example of an quantitative variable is costs or energy reduction. Some qualitative values are quality of space and improve facility management.

One criteria, specified by the property manager, investor and tenant manager, is extraordinary. The criterion 'tenant satisfaction' is mentioned by the property manager and investor and the criterion 'user satisfaction' is mentioned by the tenant manger. 'Tenant satisfaction' is a quantitative variable based on the scores of the tenant.

For example, if an alternative gets a tenant preference score of 80, the property manager scores his criterion 'tenant satisfaction' with 100. A tenant preference score below 40 is scored 0 and a tenant preference score of 60 is scored 50 by the property manager.

User perspective

For the user perspective another approach was used. Approximately 2000 people occupy the SHG which makes it is too time consuming to interview all users. Therefor a panel of department managers is made who represent their office floors. Five managers were interviewed, one of which is the property manager and decision-maker. The interviewed users were very consistent. They all stated that the availability of rooms, wayfinding and layout were a problem. One user stated the occupancy of the SHG was too high and another said that user friendliness should be taken into account.

The stakeholders all stated that they were able to include the perspectives of their colleagues. For example, the asset manager on the fourth floor stated that they often make use of (short-term) external partners, which is very common in this building. Those external employees have difficulty finding their way in the building.

In the process of conducting the interviews, a new data set became available from a research about the quality of the office, conducted by the employee committee. The employee committee had sent a survey to all Schiphol employees working in the different buildings, of which the SHG is the largest group of respondents.

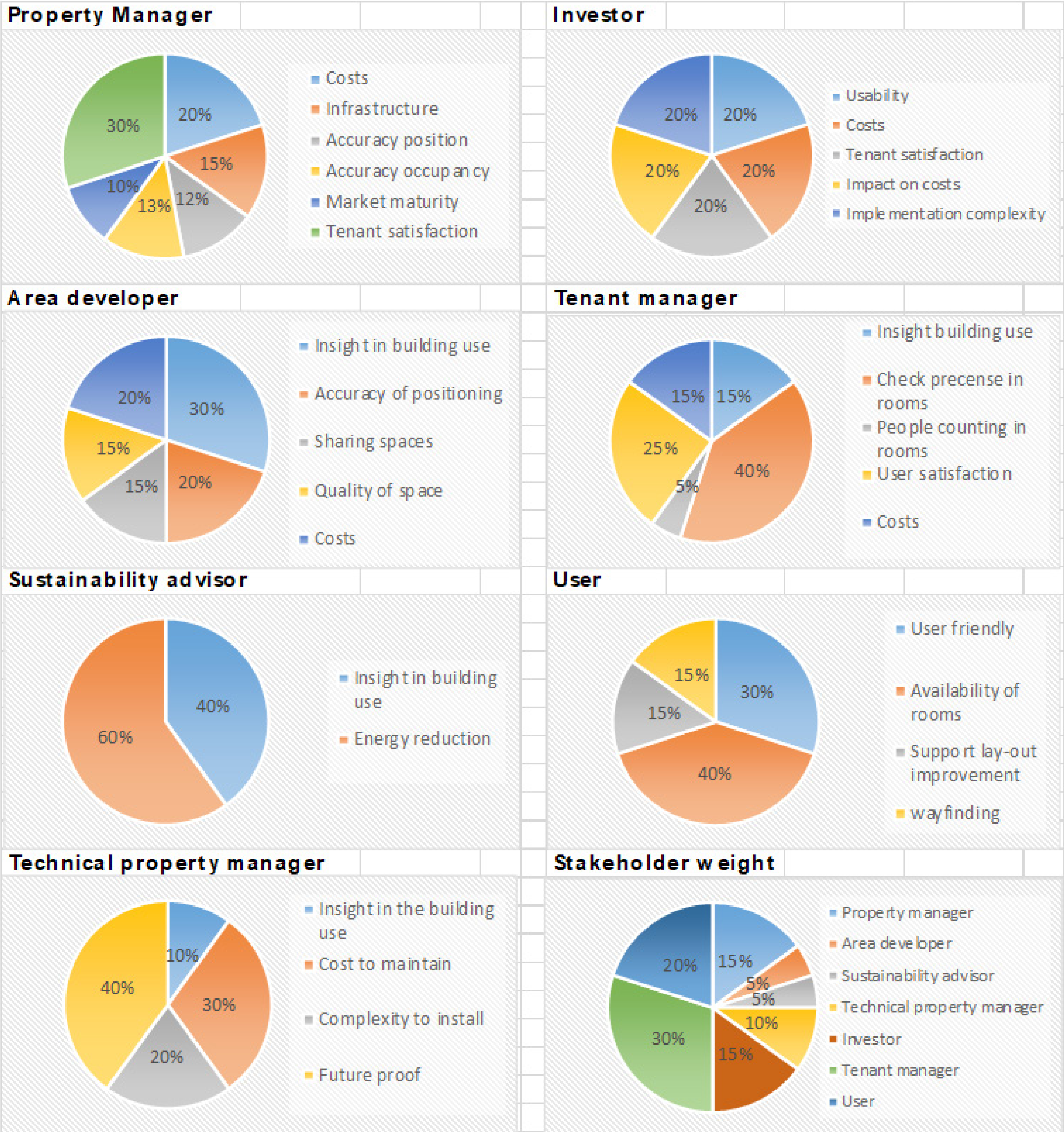


Figure 4.7. Criteria and stakeholder weight

4.2.5 Select the design alternatives

The selection of design alternatives was a supply oriented process. Based on the scope of the project, 12 indoor poisoning smart system suppliers were invited by Schiphol Real Estate. Each supplier presented their product and was asked how their product would be implemented in the building. The supplier provided the principal design of their product, which was refined into a conceptual design by the researcher, including consult of smart building experts (see figure 4.8). Each design is a complete concept as discussed in the theory chapter 'scope' (p.32). This way the conceptual designs are unambiguously which makes them easy to assess if they comply to the scope.

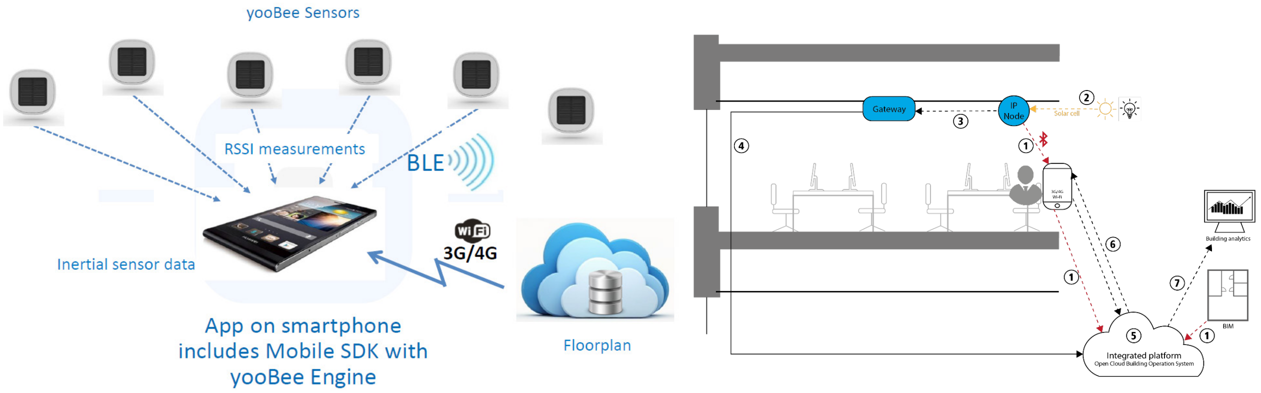


Figure 4.8.Left: principal design. Right: conceptual design

The conceptual designs were send back to the suppliers to assess the design. Feedback was given and the alternatives were finalised.

Out of the 12 alternatives, a selection of eight alternatives was made. All alternatives focus on indoor positioning and provide a complete solution (see paragraph smart building design). All feasible suppliers are able to integrate with the existing physical properties, infrastructure and building systems, comply with the privacy and security codes, are mature and are scalable.

Two of the four infeasible alternatives did not match the scope of the project. One was immature and one was not able to continue with the research.

All feasible design alternatives are described and summarized in order to provide the stakeholders with necessary information. These documents are send to all stakeholders to prepare for the next interview. The description of the eight design alternatives can be found in appendix A (a separate document).

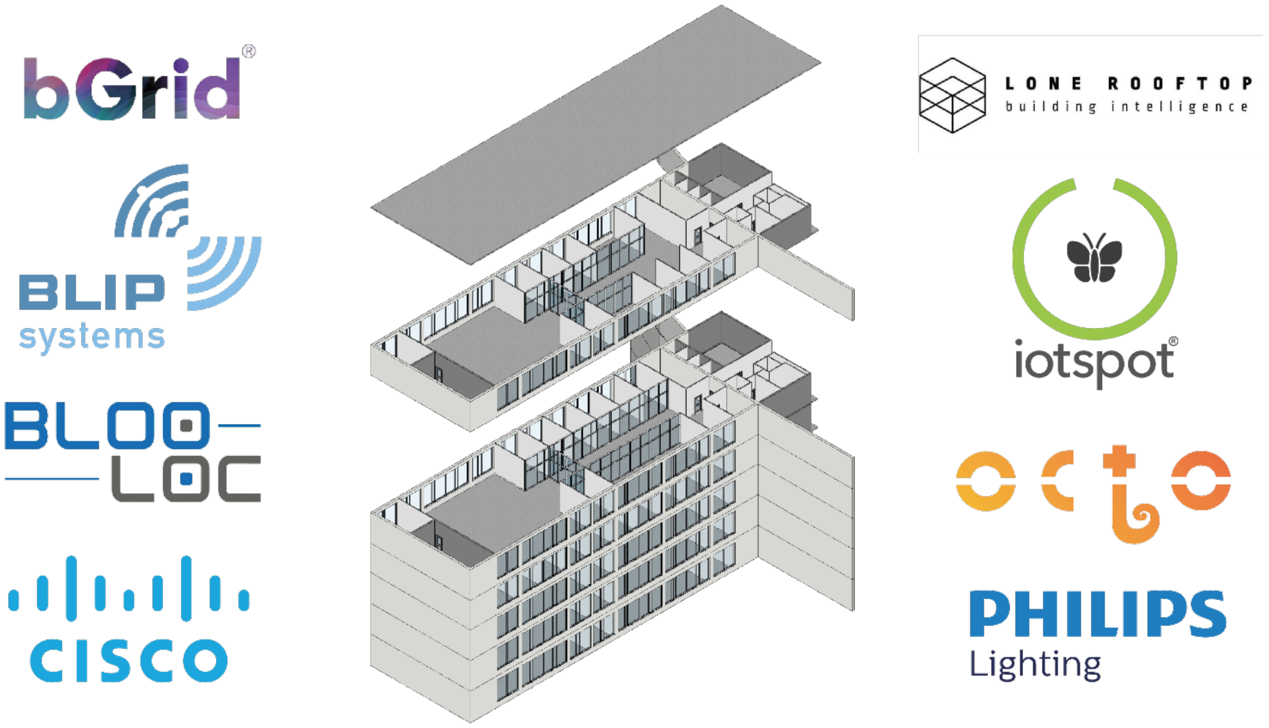
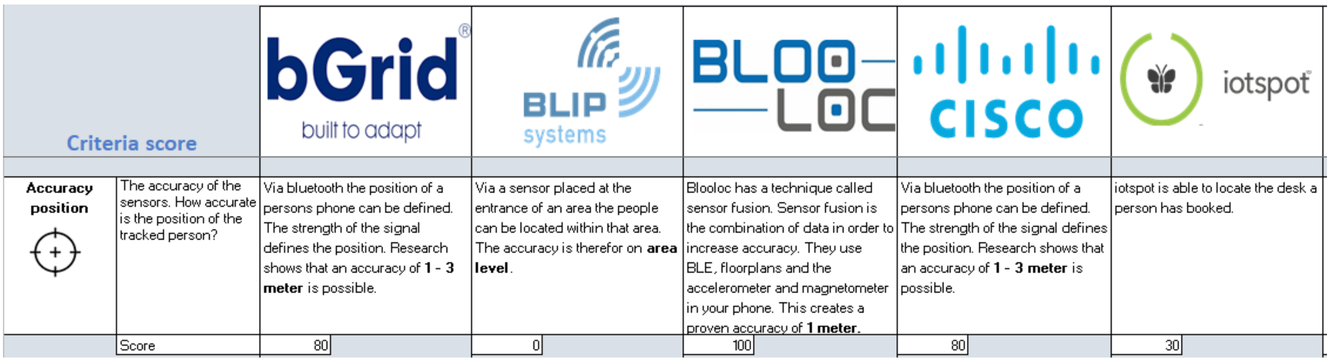


Figure 4.9 Alternatives and 3D view of the office plan

4.2.6 Rating the design alternatives

Rating the alternatives is done by scoring each alternative or as secondary option with the Lagrange curve.

The stakeholders prepared this interview by reading through the design alternatives information sheets. Based on this information and their expertise the stakeholder rated their criteria. The stakeholder was asked to rate the most preferred alternative 100, the least preferred 0 and the rest in between. During the interview it was possible to ask question and discuss the alternatives in order to accurately rate the alternatives.



Criteria score		bGrid built to adapt	BLIP systems	BLOOLOC	CISCO	iotspot
Accuracy position	The accuracy of the sensors. How accurate is the position of the tracked person?	Via bluetooth the position of a persons phone can be defined. The strength of the signal defines the position. Research shows that an accuracy of **1 - 3 meter** is possible.	Via a sensor placed at the entrance of an area the people can be located within that area. The accuracy is therefor on **area level**.	Blooloc has a technique called sensor fusion. Sensor fusion is the combination of data in order to increase accuracy. They use BLE, floorplans and the accelerometer and magnetometer in your phone. This creates a proven accuracy of **1 meter.**	Via bluetooth the position of a persons phone can be defined. The strength of the signal defines the position. Research shows that an accuracy of **1 - 3 meter** is possible.	iotspot is able to locate the desk a person has booked.
	Score	80	0	100	80	30

Figure 4.10 Preference rating

Two types of criteria were rated using the Lagrange curve: costs and tenant/user satisfaction. The reason for this is change. The costs are not officially agreed upon and may change. The satisfaction criteria depends on the preference scores of other stakeholders, which may change as well. By using the Lagrange curve change is allowed to happen without redoing the rating process. The curve was established by asking the stakeholder to state what value would get a score of 0 and what value would get a score of 100. The stakeholder would than establish the intermediate by asking what score the intermediate value would get. The stakeholders that established a preference curve were the property manager, area developer, investor and tenant manager (see figure 4.11).

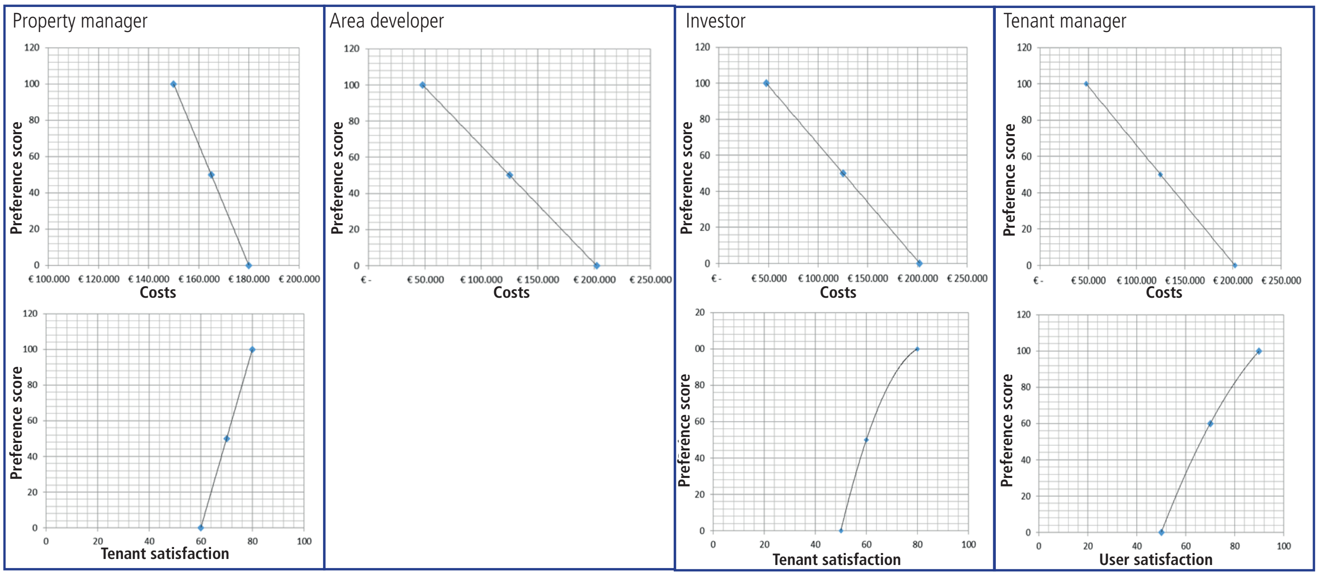


Figure 4.11. Lagrange curves stakeholders

4.2.7 Rank list

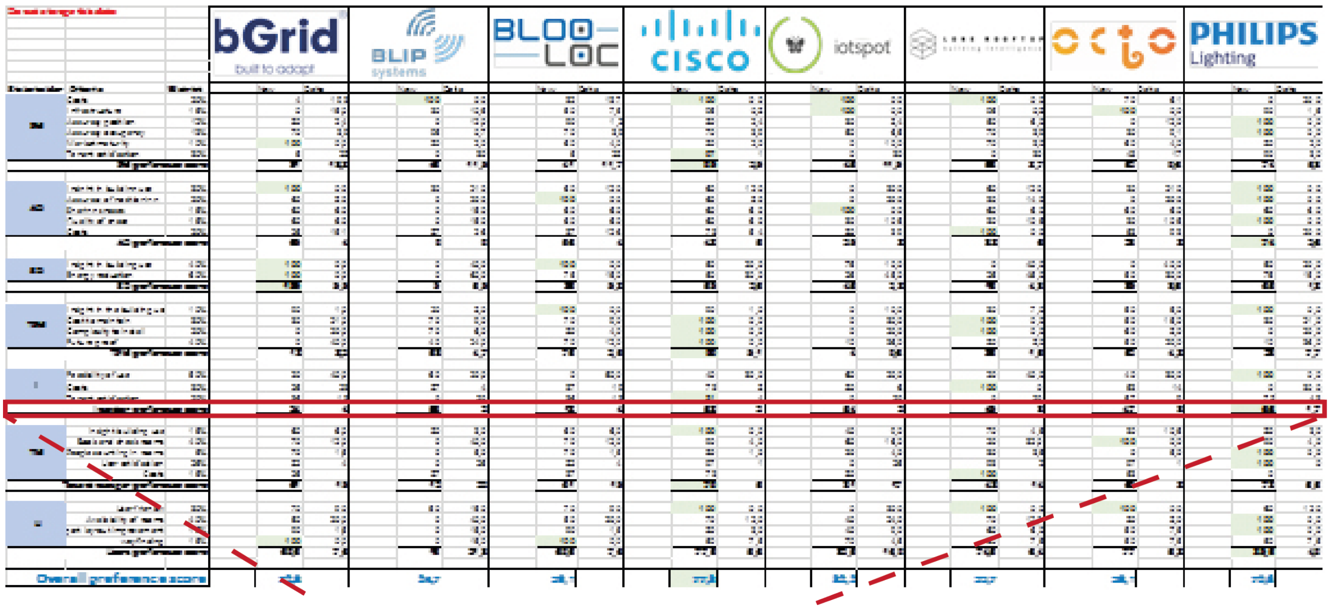
The output of the model is a sheet describing the score of each criterion, each stakeholder and all stakeholders combined. The primary rank list that will be used to support decision-making is the overall preference score. The list is ranked from high to low, in which the highest score is the most preferred option and recommended to be implemented in the building, in this case Cisco (see figure 8.10).

Ranklist
79,6 - Cisco
71,1 - Philips
68,0 - Octo
67,3 - Lone rooftop
60,1 - BLooloc
52,1 - bGrid
37,2 - iotspot
30,7 - BLIP & Brickstream

Figure 4.12 Rank list

The second source of information is the rank list for each stakeholder (see figure 4.12). The information may be of importance when discussing the recommended alternative with the stakeholder. When the recommended alternative is different than the most preferred option of a stakeholder it may lead to discontent and the stakeholder may not agree with the recommended option. This must be taken into account when using this information.

For example, the image below shows the difference between the recommended option and the most preferred option of the investor. In the model, the weight of each stakeholder is taken into account, but not their power. The investor may have power over the purchase of the alternative. If he does not agree with the recommended option, he may use this power to force his most preferred option



Ranklist Overall preference score
79,6 - Cisco
71,1 - Philips
68,0 - Octo
67,3 - Lone rooftop
60,1 - BLooloc
52,1 - bGrid
37,2 - iotspot
30,7 - BLIP & Brickstream

Preference score investor (as example)
76- Philips
71 - Cisco
66 - Octo
52 - iotspot
49 - Lone rooftop
45 - BLIP & Brickstream
26 - Blooloc
22 - bGrid

Figure 4.13. Rank list comparison

After the output was shown to the decision-maker, the decision-maker agreed that the most preferred alternative is best for this case. The rank list correlated with his assumptions. The decision-maker does not expect conflict and is open to discuss the top 3, which contains almost the same alternatives for each stakeholder. The rank list (especially the top 3) can be used to support further discussion for a pilot case.

4.2.8 Combine alternatives

An extra possible output is to combine the alternatives into an 'optimum new alternative'. The new alternative consists of the elements that scored highest on each criterion. The output is a complex combination of alternatives, which does not directly give you a new optimum design, but rather a list of the alternative that scores best on each criterion. In order to find the new alternative, features of different alternatives need to be combined. This is done by discussing the list shown left in figure 4.14 with the decision-maker and smart building experts. The purpose of the discussion is to select features of other alternatives that may be included in the most preferred alternative (Cisco). By combining features of different alternatives, the most preferred option may be further improved. Note, that this is not calculated.

The features can be used as input for the discussion with the most preferred - recommended - alternative in order to see if the most preferred can be even better aligned with the preferences of the stakeholders (see figure 8.12).

Five features were selected in the discussion: communication, PIR sensing, personalized sensing, camera sensing and climate sensing. Two methods provide insight in immediate improvement (communication and PIR). Three methods provide insight to improve the recommended alternative in the future (personalized, camera and climate).

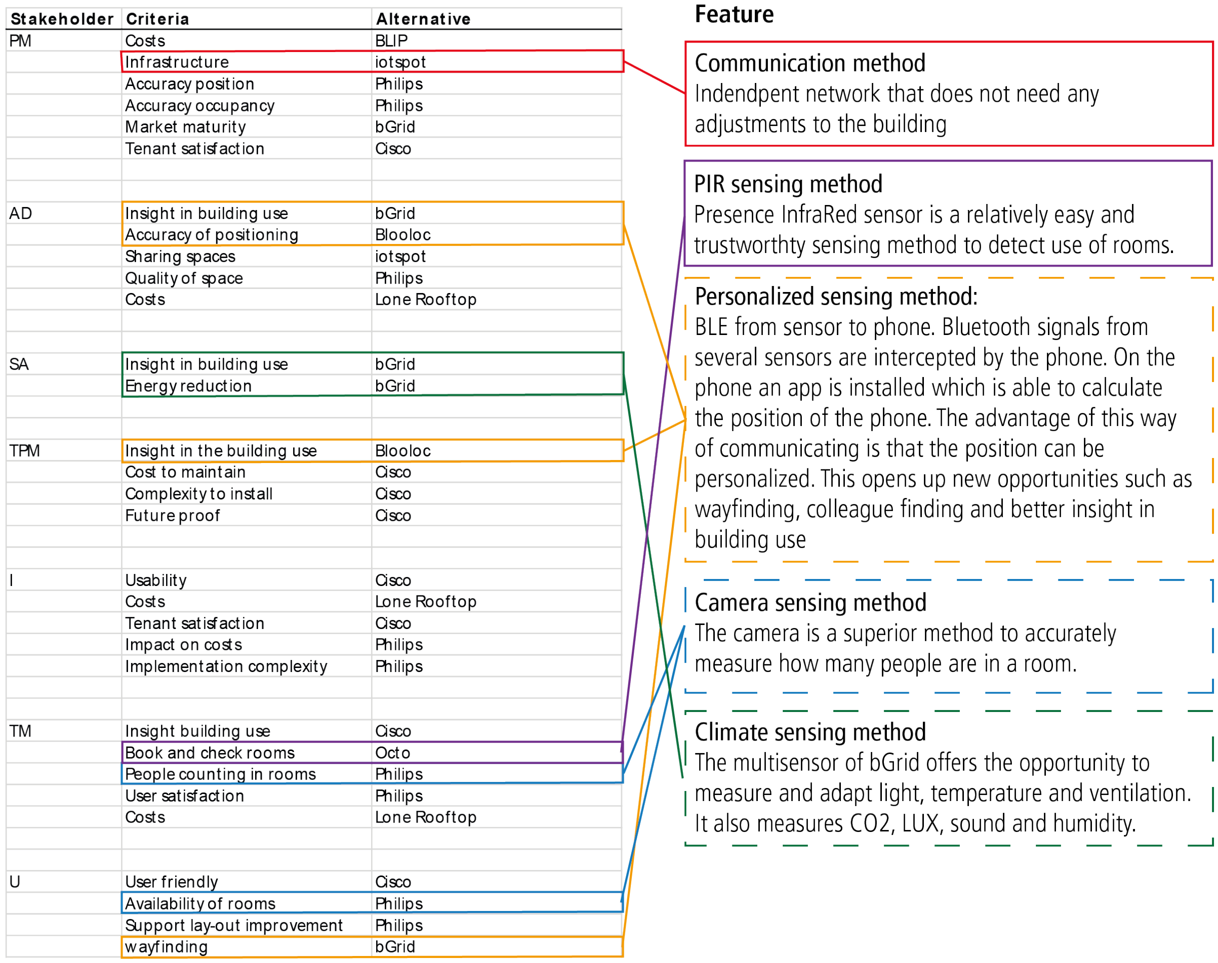
Iotspot (and also Octo) are preferred for their communication method. They make use of existing external communication networks such as cellular networks (4G) or LoRa. These types of communication do not put any stress on the existing building network. For further discussion with Cisco, the question can be asked if Cisco can make use of this type of communication as well, or come close to.

The Infrared sensor (PIR) is a very accurate measure when it comes to detecting presence in a room. It is preferred over Bluetooth or Wi-Fi because it has no error margin for people not having a mobile device with them or no Bluetooth or Wi-Fi enabled. Since detecting presence in a room has a very high weight and because Cisco scores 70 on this criterion, there is still much room to improve. Therefor an immediate point of discussion with Cisco would be to see if the possibility of including PIR sensors exists and if it would improve the overall preference score.

The personalized sensing method is a much bespoken subject in smart building concepts. It collects highly accurate information about who was/is where in the building and how to get from your location to another person. It is a difficult feature which cannot be included easily. Therefor it does not form a immediate point of improvement but could be kept in mind to foresee future improvements.

The camera is the best method to perform people counting in a room. Because of the low importance of this feature it is not of priority. If this becomes of higher priority, Cisco will be asked if they can include a camera in their design. If so, the camera could be an extension to the design alternative of Cisco.

The scope of the project is indoor positioning. However, some alternatives also include climate sensors in their nodes. bGrid offers the possibility to adapt light and temperature by using your phone. Since this is not the scope of the project it is not a priority but for further plans is may be good to discuss this subject to foresee any future changes.



Stakeholder	Criteria	Alternative
PM	Costs	BLIP
	Infrastructure	iotspot
	Accuracy position	Philips
	Accuracy occupancy	Philips
	Market maturity	bGrid
	Tenant satisfaction	Cisco
AD	Insight in building use	bGrid
	Accuracy of positioning	Blooloc
	Sharing spaces	iotspot
	Quality of space	Philips
	Costs	Lone Rooftop
SA	Insight in building use	bGrid
	Energy reduction	bGrid
TPM	Insight in the building use	Blooloc
	Cost to maintain	Cisco
	Complexity to install	Cisco
	Future proof	Cisco
I	Usability	Cisco
	Costs	Lone Rooftop
	Tenant satisfaction	Cisco
	Impact on costs	Philips
	Implementation complexity	Philips
TM	Insight building use	Cisco
	Book and check rooms	Octo
	People counting in rooms	Philips
	User satisfaction	Philips
	Costs	Lone Rooftop
U	User friendly	Cisco
	Availability of rooms	Philips
	Support lay-out improvement	Philips
	wayfinding	bGrid

Feature

Communication method
Indendpent network that does not need any adjustments to the building

PIR sensing method
Presence InfraRed sensor is a relatively easy and trustworthty sensing method to detect use of rooms.

Personalized sensing method:
BLE from sensor to phone. Bluetooth signals from several sensors are intercepted by the phone. On the phone an app is installed which is able to calculate the position of the phone. The advantage of this way of communicating is that the position can be personalized. This opens up new opportunities such as wayfinding, colleague finding and better insight in building use

Camera sensing method
The camera is a superior method to accurately measure how many people are in a room.

Climate sensing method
The multisensor of bGrid offers the opportunity to measure and adapt light, temperature and ventilation. It also measures CO2, LUX, sound and humidity.

Figure 4.14.Combine alternatives

4.2.9 Iteration

To facilitate iteration, at the end of each interview the participant was asked if input from previous interviews is still according to satisfaction. If not, the participant was able to change the input. At the end of the procedure all stakeholder were once more asked if they feel the need to change their input. During the entire process, the stakeholders were allowed to see the input of other stakeholders and output of the model.

Iteration appeared to be a very important step in the research (see figure 4.15). All stakeholders felt the need for iteration. Many of the variables that were specified in the beginning of the process were adapted, removed or added.

Most of these changes were made during the third interview, in which they rated the alternatives and weighted the criteria. Before and during this interview the alternatives became better known to the stakeholders and based on new information and discussion all stakeholders felt the need to change their variables. The adapted variables were rated and weighted during the interview. After the interview, the property manager and investor asked if their input sheet could be send to them to rethink the input given. The investor did not yet assigned weights because he wanted to revise the criteria.

In the following interview (interview 4: iteration) the stakeholders were shown the results and asked if they are satisfied with their input. Both the property manager and investor revised their input beforehand and indicated the need for changes. The property manager changed multiple criteria and redid the weights. The area developer added the criterion costs based on the input of other stakeholders and revised the weights. The investor changed multiple variables and assigned weights. The tenant manager added the criterion user satisfaction based on the input of other stakeholders and revised the weights. The users revised their variables based on the survey that became available.

After the fourth interview, only the property manager wanted to revise the stakeholder weights as it was not brought up during the fourth interview. The weights of several stakeholders was changed based on a discussion with the researcher.

Iteration ensured the removal of 17 variables, combining four variables into one, changing the definition of three variables and adding 10 variables (see figure 4.16). After iteration 36 variables are established of which six are constraints and 31 are criteria. The variable 'market maturity is still a constraint and criterion.

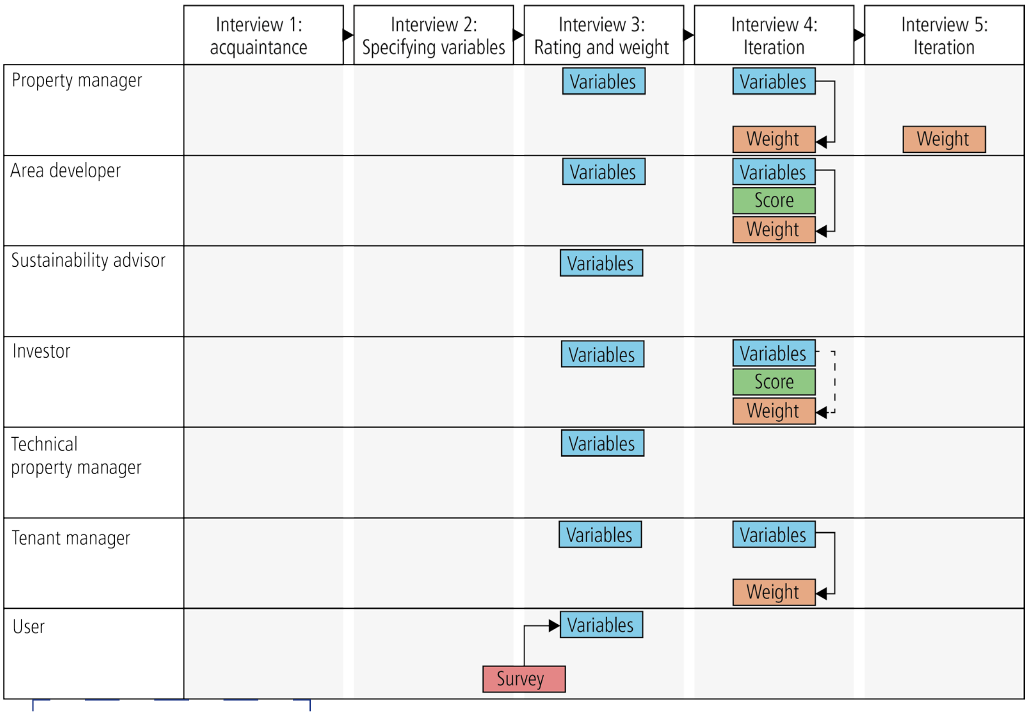
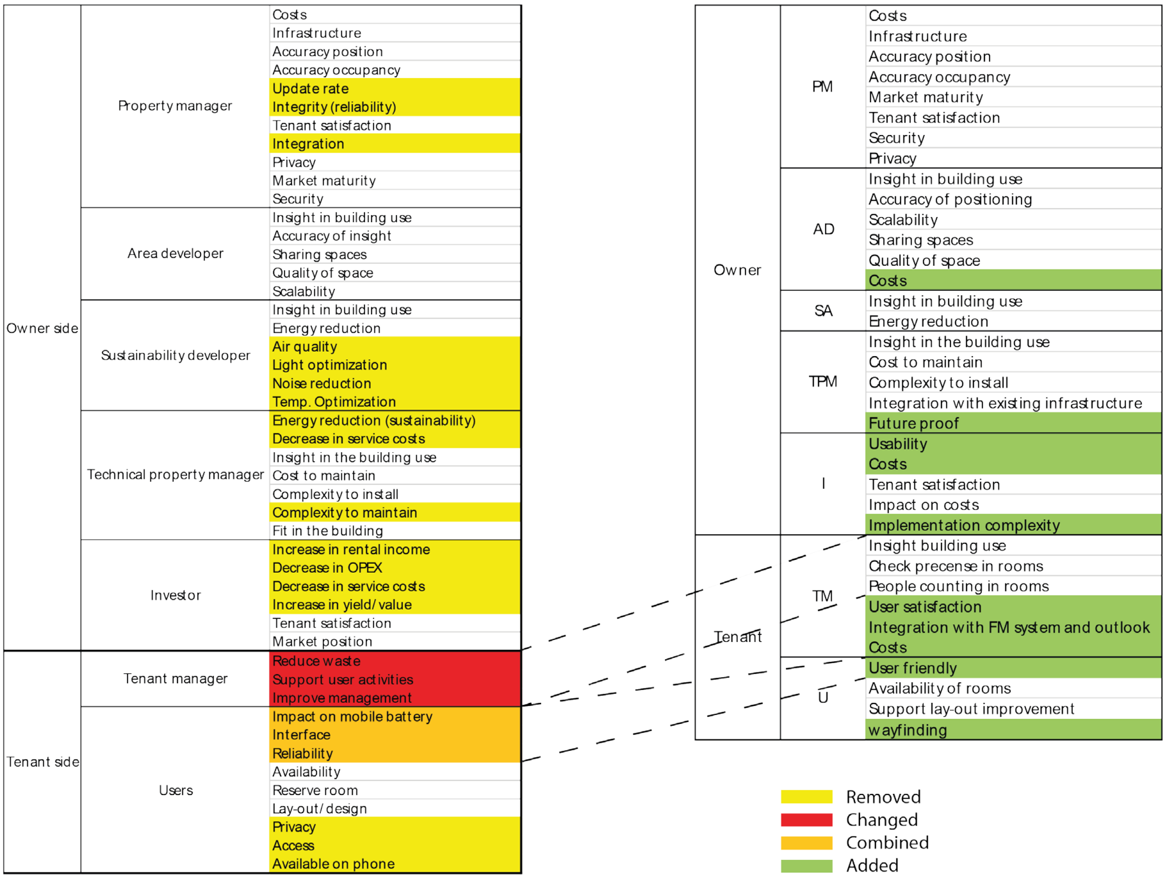


Figure 4.15.Iteration

During the research it became evident that iteration was of great importance. It seemed that due to a lack of information at the beginning, the stakeholders specified variables that later on did not match their intentions. This became evident during the third interview. Even after the third interview iteration was still of importance because the property manager and investor stated that they wanted to rethink their input. Other stakeholders made use of iteration because they saw the input of others and agreed that these variables are of importance. Without iteration the input would not be formulated as intended, which is in line with the conclusion of the PAS approach (Arkesteijn et al., 2017: p. 258).



Owner side	Property manager	Costs
		Infrastructure
		Accuracy position
		Accuracy occupancy
		Update rate
		Integrity (reliability)
		Tenant satisfaction
		Integration
		Privacy
		Market maturity
		Security
	Area developer	Insight in building use
		Accuracy of insight
		Sharing spaces
		Quality of space
		Scalability
	Sustainability developer	Insight in building use
		Energy reduction
		Air quality
		Light optimization
		Noise reduction
		Temp. Optimization
	Technical property manager	Energy reduction (sustainability)
		Decrease in service costs
		Insight in the building use
		Cost to maintain
		Complexity to install
		Complexity to maintain
		Fit in the building
	Investor	Increase in rental income
		Decrease in OPEX
		Decrease in service costs
		Increase in yield/ value
		Tenant satisfaction
		Market position
Tenant side	Tenant manager	Reduce waste
		Support user activities
		Improve management
	Users	Impact on mobile battery
		Interface
		Reliability
		Availability
		Reserve room
		Lay-out/ design
		Privacy
		Access
		Available on phone

Owner	PM	Costs
		Infrastructure
		Accuracy position
		Accuracy occupancy
		Market maturity
		Tenant satisfaction
		Security
		Privacy
	AD	Insight in building use
		Accuracy of positioning
		Scalability
		Sharing spaces
		Quality of space
		Costs
	SA	Insight in building use
		Energy reduction
	TPM	Insight in the building use
		Cost to maintain
		Complexity to install
		Integration with existing infrastructure
		Future proof
	I	Usability
		Costs
		Tenant satisfaction
		Impact on costs
		Implementation complexity
Tenant	TM	Insight building use
		Check precense in rooms
		People counting in rooms
		User satisfaction
		Integration with FM system and outlook
		Costs
	U	User friendly
		Availability of rooms
		Support lay-out improvement
		wayfinding

🟨 Removed
🟥 Changed
🟧 Combined
🟩 Added

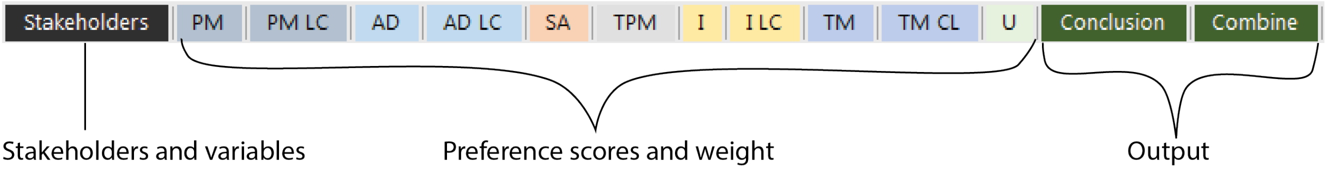
Figure 4.16. Process of iteration regarding the variables

4.3 Model

At the beginning of the research the ambition was expressed to create a mathematical model to support decision-making in a multi-criteria problem. The mathematical model is created in Excel with the purpose to be handled by the researcher. The model is functional and does not include a guide or interface for other users. This chapter is the explanation of the model and guides you through all the tabs of the Excel model.

The Excel model consists of the following tabs:

- The stakeholder selection + variables
- The preference scores + weight
- Output



4.3.1 Stakeholder selection + variables

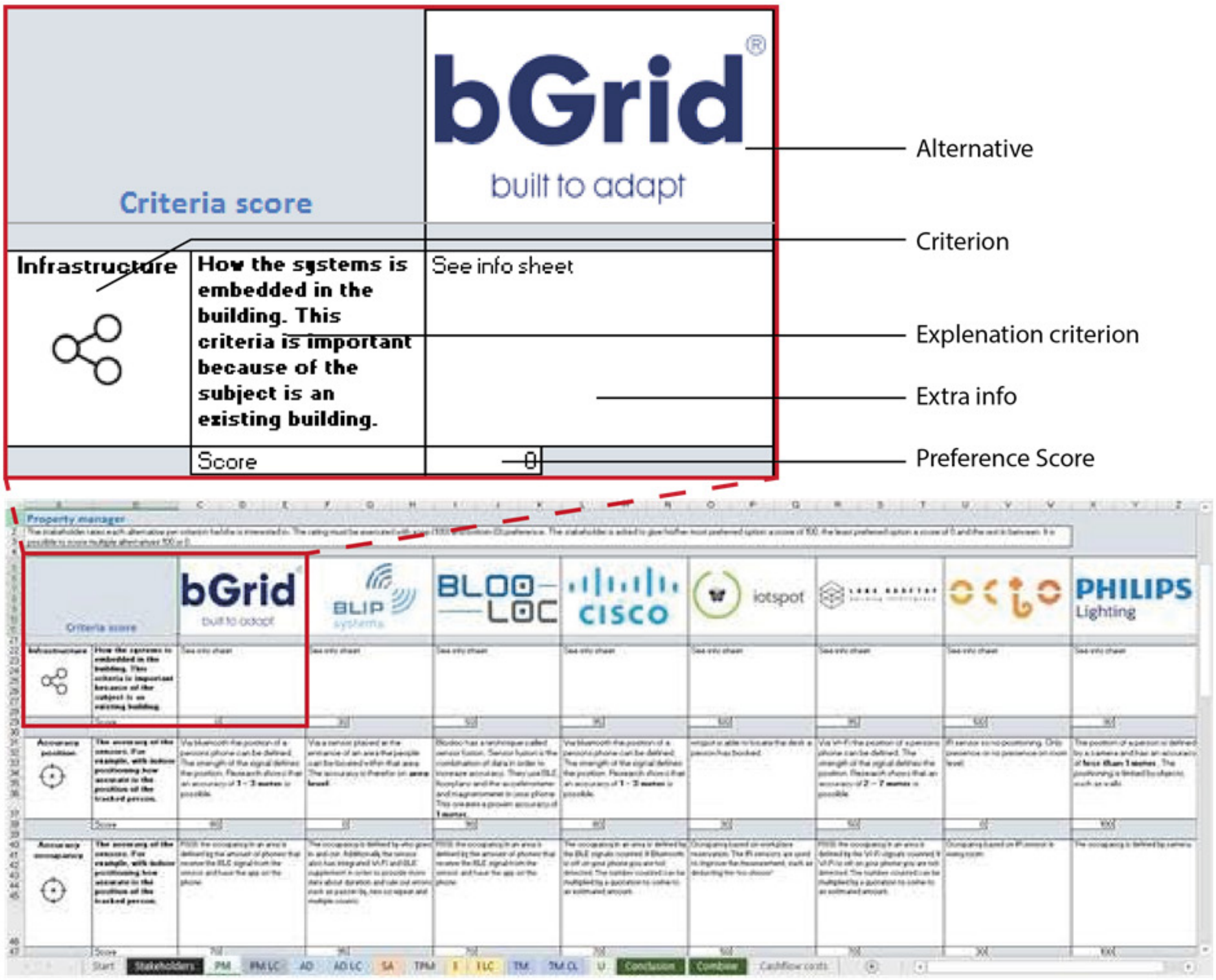
The stakeholder selection is summarized in the model. It provides an overview of all the variables that are of interest to the stakeholders. It does not include any calculation.

4.3.2 Preference scores

Rating the alternatives

For each stakeholder a tab is created including their criteria and all feasible alternatives. In short each criterion is explained. Below each alternative there is room for extra explanation relevant to the criterion. At the bottom of each explanation there is a cell for entering the preferred score.

Extra information is given in the form of information sheets. These are given to the stakeholder beforehand in order to prepare for the rating of alternatives. The information can be discussed during the process and extra information can be given.



Criteria score

Infrastructure

How the systems is embedded in the building. This criteria is important because of the subject is an existing building.

See info sheet

Score 0

Figure 4.17 Rating of the alternatives tab

Lagrange curve

For the criteria costs and tenant/user satisfaction the Lagrange curve is used. The curve consist of a top, intermediate and bottom score, which are established by the stakeholder. The stakeholder is asked to give the value to which he would give a score of 100, 0 and 50. Note that he stakeholder can also be asked to give a score to the value intermediate value (In the example the intermediate value is 100.000 + 180.000 / 2 = 140.000. The stakeholder has to give a score to this value).

The curve (graph) is made using a standard function in Excel (see figure 4.18). The graph is created by selecting the values and scores and to format an X,Y scatter chart in Excel. The line is created by selecting one of the points and format a polynomial line. The graph functions as a visualization of the Lagrange curve formula

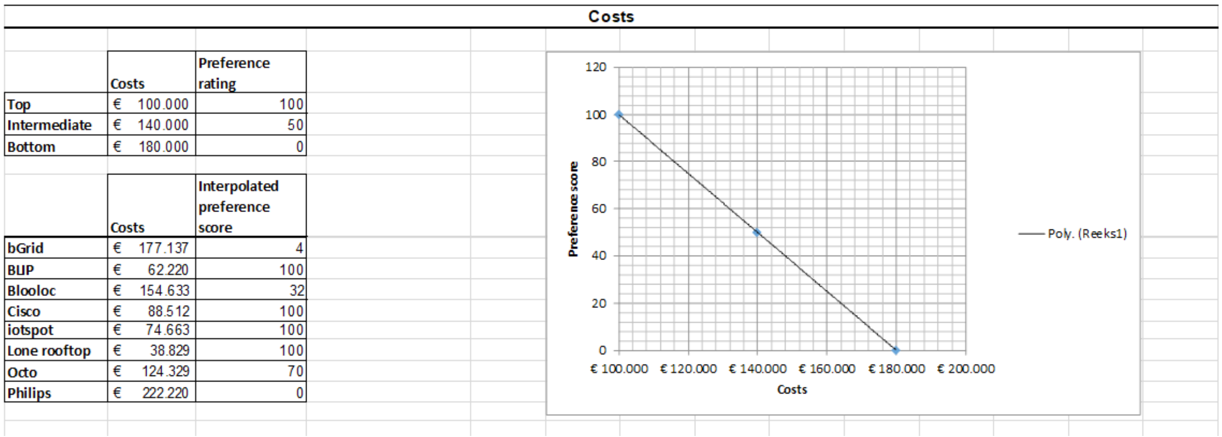
The interpolated preference scores are calculated using the Lagrange curve formula:

$$P(x) = ((x - x1)(x - x2)/(x0 - x1)(x0 - x2)) * y0 + ((x - x0)(x - x2)/(x1 - x0)(x1 - x2)) * y1 + ((x - x0)(x - x1)/(x2 - x0)(x2 - x1)) * y2\ldots$$

However the formula has a limitation. It has the possibility to overshoot.

e.g., the top value of €100.000 get a preference score of 100. An alternative costing €80.000 will also need to get a score of 100. Using the above formula will give a score of 125, which is out of the preference score range (0 – 100). The same goes for the other side of the range. A system costing €180.000 or more should get a score of 0. However, a system costing €200.000 gets a score of -25.

To solve this problem, visual basic is used. Visual basic is a programming environment to support formulas and graphical applications. In visual basic the Lagrange curve can be extended by implementing the 'IF' function. IF function is useful when a value is higher than the top value or lower than the bottom value. It prevents the curve to overshoot (go outside the preference score range). In the above example, the value of €80.000 will be automatically set to 100 and the value of €200.000 will be set to 0.



Costs

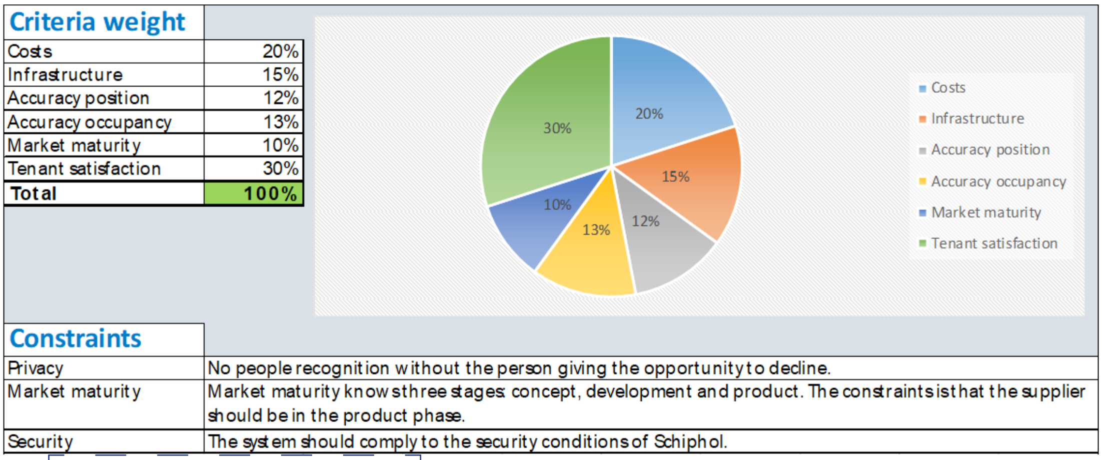
	Costs	Preference rating
Top	€ 100.000	100
Intermediate	€ 140.000	50
Bottom	€ 180.000	0

	Costs	Interpolated preference score
bGrid	€ 177.137	4
BLIP	€ 62.220	100
Blooloc	€ 154.633	32
Cisco	€ 88.512	100
iotspot	€ 74.663	100
Lone rooftop	€ 38.829	100
Octo	€ 124.329	70
Philips	€ 222.220	0

Figure 4.18. Lagrange curve

4.3.3 Weights

The weights of all criteria combined should equal 100%. The stakeholder will fill in the weight of each criterion. The total will turn green if exactly 100% is reached. To the right, a pie graph is used to visualize the criteria weight.



Criteria weight	
Costs	20%
Infrastructure	15%
Accuracy position	12%
Accuracy occupancy	13%
Market maturity	10%
Tenant satisfaction	30%
Total	**100%**

Constraints	
Privacy	No people recognition without the person giving the opportunity to decline.
Market maturity	Market maturity knows three stages: concept, development and product. The constraints is that the supplier should be in the product phase.
Security	The system should comply to the security conditions of Schiphol.

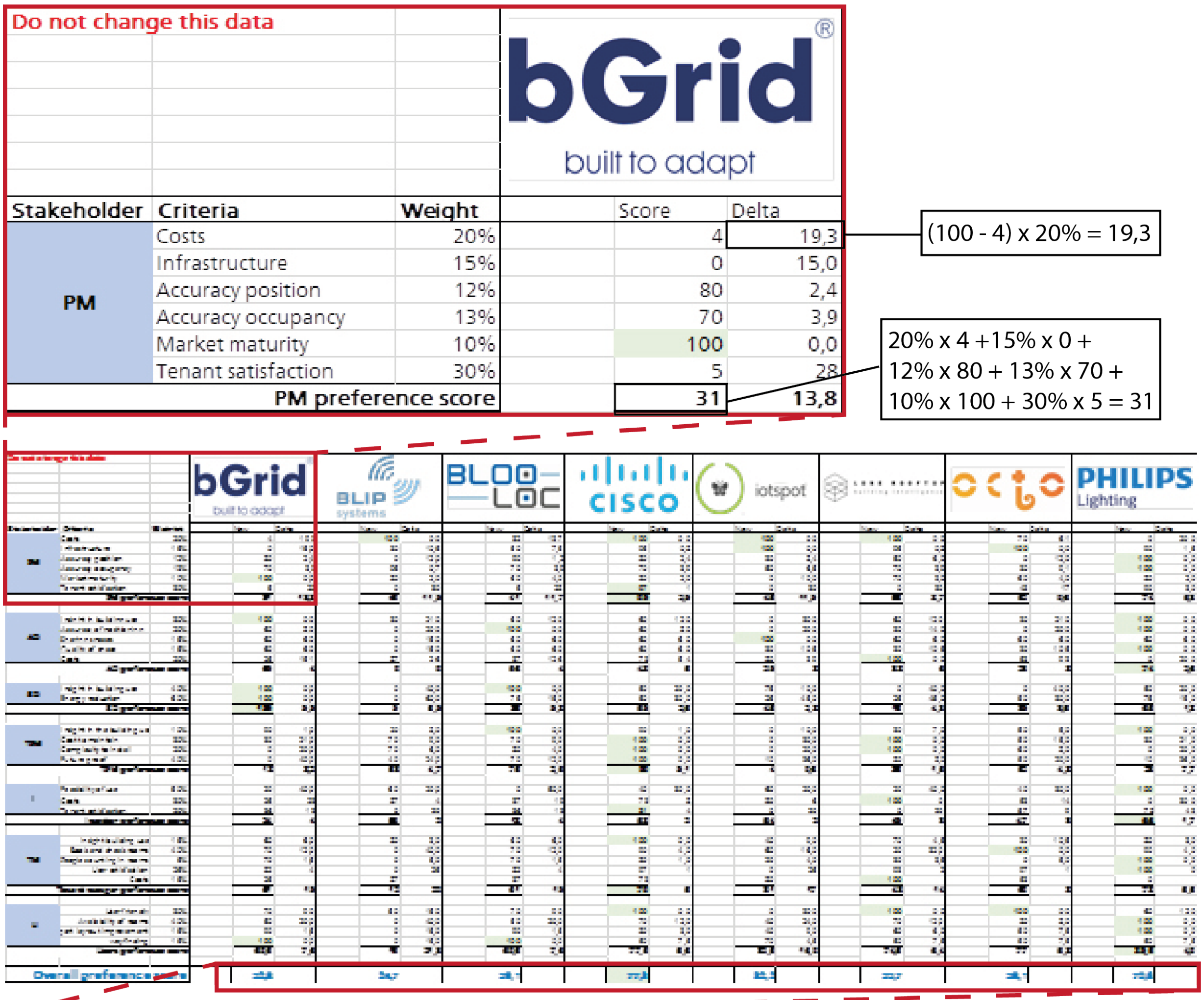
Figure 4.19. Criteria weight

4.3.4 Conclusion (Rank list)

The conclusion tab is where all input from the stakeholders comes together. The throughput as described in the principle structure of the model is calculated here. Two results are shown in this tab: the stakeholder preference score and the overall preference score. Additionally the delta is given, which is the weighted gap between preference score and maximum preference score.

The stakeholder preference score is shown at the top figure 9.5. It is the sum of all weighted scores. The stakeholder can see for each criterion how the alternative scored and easily compare them. If an alternative scored highest on a criterion it is highlighted in green. The alternative that scored highest on all criteria of the stakeholder is also highlighted in green.

At the bottom of the conclusion tab the overall preference scores are shown. The overall preference score is the weighted sum of all stakeholder preference scores (Note that the weight of the stakeholder is hidden). The highest overall preference score is highlighted in green. A rank list can easily be made from these results (see bottom figure 4.20).



Do not change this data

Stakeholder	Criteria	Weight	Score	Delta
PM	Costs	20%	4	19,3
	Infrastructure	15%	0	15,0
	Accuracy position	12%	80	2,4
	Accuracy occupancy	13%	70	3,9
	Market maturity	10%	100	0,0
	Tenant satisfaction	30%	5	28
	PM preference score		31	13,8

(100 - 4) x 20% = 19,3

20% x 4 +15% x 0 +
12% x 80 + 13% x 70 +
10% x 100 + 30% x 5 = 31

79,6 - Cisco
71,1 - Philips
68,0 - Octo
67,3 - Lone rooftop
60,1 - BLooloc
52,1 - bGrid
37,2 - iotspot
30,7 - BLIP & Brickstream

PM pref. score Cisco x PM weight + AD pref. score Cisco x AD weight + etc. = 79,6

Figure 4.20 Conclusion tab

4.3.5 Limitation

A limitation in the model is the Lagrange curve. The curve can give negative preference scores or scores above the maximum (often 100). This problem presents itself when the intermediate is far from the linear between the top and bottom reference. When this happens the Lagrange curve is not suitable for establishing preference scores. The example below illustrates the problem. On the left a linear line is created because the intermediate (30,25) is exactly on the y = -ax + b formula. In the middle graph, the intermediate (30,40) moves slightly away from the linear and a curve is created. In the right graph, the intermediate (30,75) moves further away from the linear and the Lagrange problem occurs. The curve goes above the maximum of 100 which is unacceptable in the research. Thus, it seems that the further the intermediate is from the linear, the more likely it becomes that the Lagrange problem occurs and the preference score cannot be established.

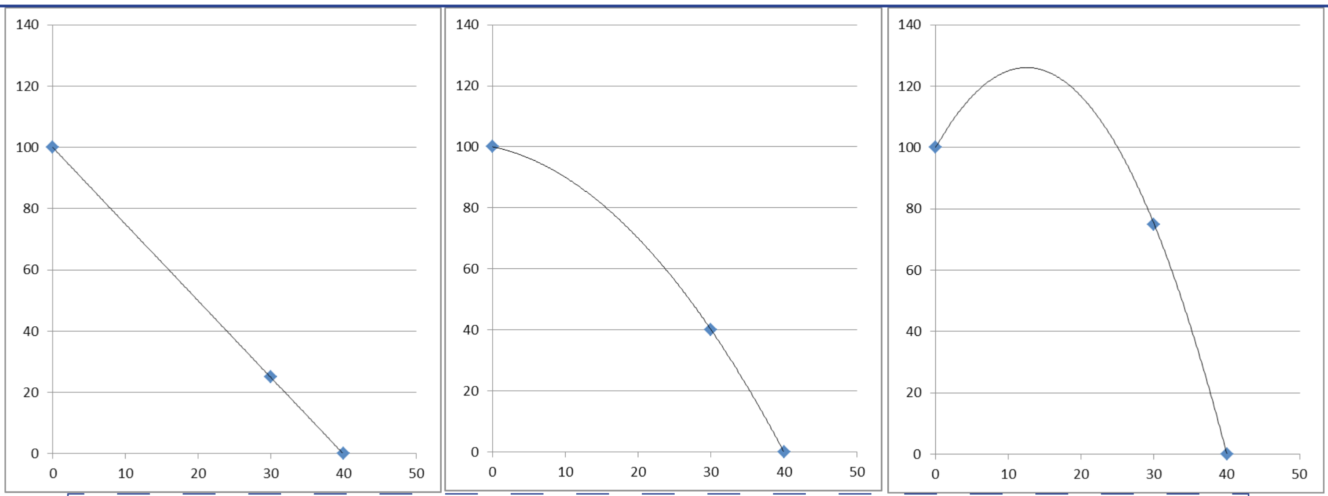
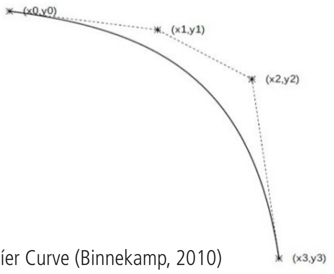


Figure 4.21. Lagrange problem

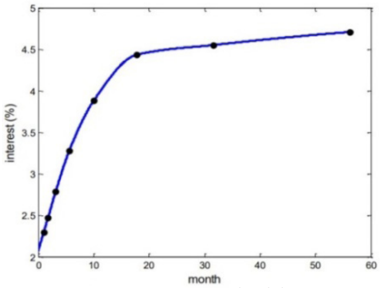
Alternative for the Lagrange curve

Ruud Binnekamp (2010) recommends in his dissertation a Bezíer Curve to exclude this problem. First, the stakeholder has to decide on the coordinate of the top and bottom reference. The stakeholder then uses two intermediate control points to shape the curve until its slope corresponds to how the stakeholder relates decision variable values to preference ratings (see top right figure). However, this method is more difficult for both researcher and participants.



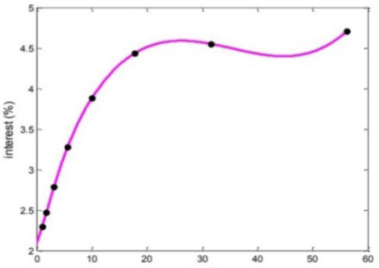
Bezíer Curve (Binnekamp, 2010)

Another solution in the field of mathematics is Piecewise Cubic Interpolation (PCI). The curve is made out of pieces. For each curve between two points the slope changes. In other words, the individual segments have different coefficients (Erasmus, 2007). The figure below is an example of PCI. The main advantage is that no interpolated function values outside the range of data (negative or above maximum). The downside is that the graph is not very smooth.



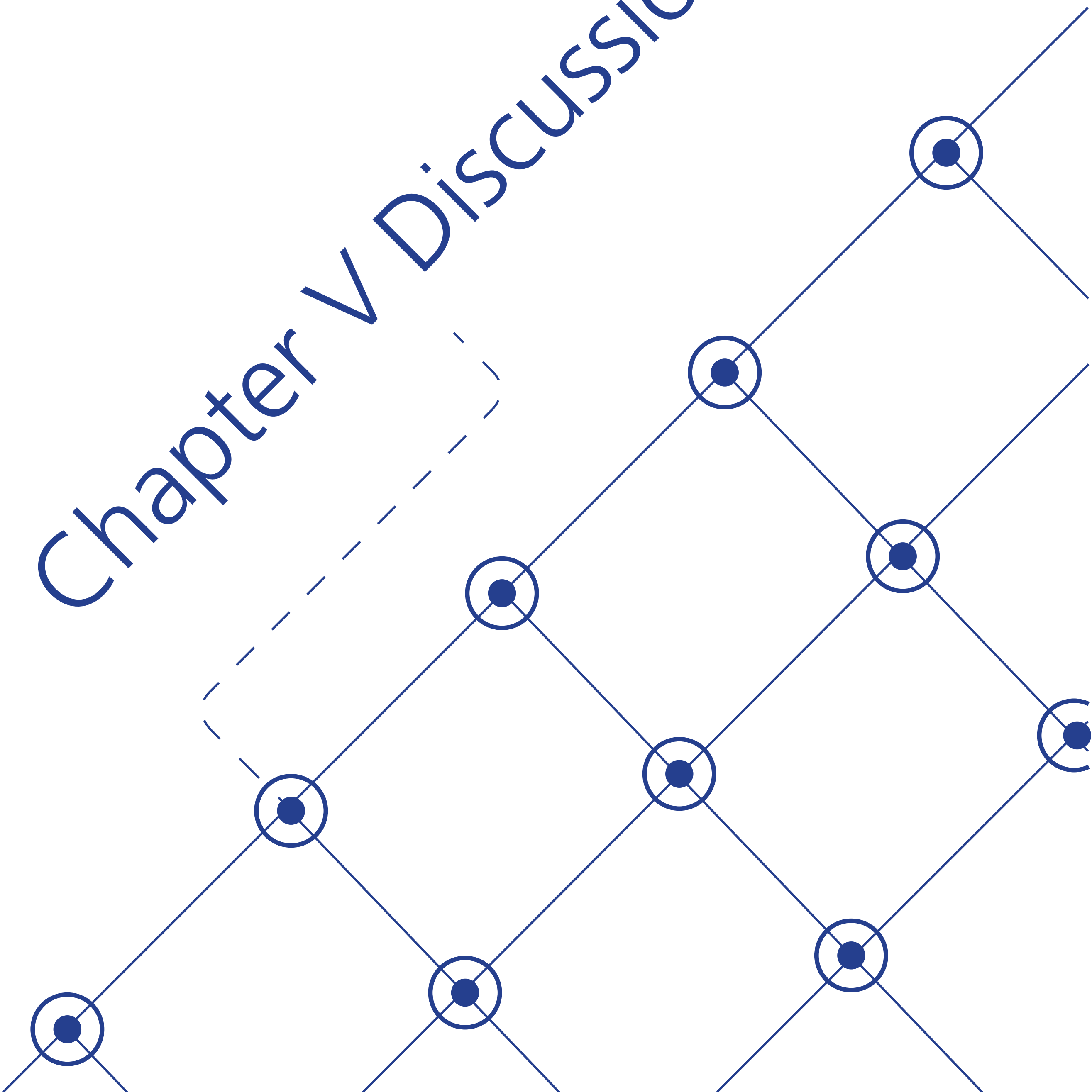
Piecewise Cubic Interpolation (PCI) (Erasmus, 2007)

The last mathematical formula that could replace the Lagrange curve is Spline. 3D models make use of splines to create smooth surfaces. For that reason it is used a lot in 3D modelling. The downside is that in extreme situations the function can overshoot data (Erasmus, 2007). Secondly, the ability to make smooth curves results in the example below in an upwards opening parabola between the last two points. This may not be in line with the preferences and the use of smooth curves may not be relevant for this research.



Spline (Erasmus, 2007)

Chapter V Discussion



5. Discussion

At the beginning of the research it was stressed that the research method, based on the PAS approach of Arkesteijn et al. (2017) and PFM, has never been tested on a subject such as smart buildings. During the research the method was (partly) evaluated with each of the participants. The evaluation of the method took place after the third and fourth interview. The method and the information available was discussed and valuable feedback was given by all participants. First, the feedback of the stakeholders will be discussed. Secondly, the observations of the author/researcher will be discussed. Based on these two evaluations, a new model is proposed for future research.

5.1 Feedback stakeholders

Interview 1: acquaintance

This interview is set up for the researcher to select the stakeholders. Each stakeholder that was of interest to the research was asked if he/she wanted to participate. The stakeholders were told that they would participate in a series of interviews. Furthermore, it was explained which input they have to give. All stakeholders wanted to participate and it was perceived that they were generally open and positive about the method.

Interview 2: specifying variables

After the second interview every interviewee is asked how they experienced the procedure of specifying the variables. It was an open question to which the interviewees could state any positive or negative experience with specifying the variables.

The answers from the interviewees on the open question in combination with my observation painted the following picture: the stakeholders were generally positive that they could specify the variables they think are important. Especially the facility managers were interested in the process of specifying variables. They acknowledged that there are certain problems in the building but struggled with translating it into clear variables. Therefor this interview is repeated once more in order for them to be satisfied with the variables they specified. The interviews helped them and were perceived as a positive session to clarify their interest.

The sustainability advisor stated that it could also be sufficient to use predefined variables based on literature about indoor positioning or smart buildings.

Interview 3: rate the alternatives and weighing the criteria

After the third interview every interviewee is asked how they experienced the procedure of rating the alternatives and weighing the criteria. It was an open question to which the interviewees could state any positive or negative experience with this step.

The most stakeholders had negative experience with rating the alternatives. The reason for this is the knowledge required to effectively give scores to the alternatives. The property manager, Area developer, Investor, Facility manager and user representative stated that they do not have sufficient knowledge to effectively rate the alternatives. Even the information sheet that was given beforehand did not give them the acquired knowledge. For example the negative feedback that was given by the different stakeholders:

"It is risky to judge the alternatives if you don't know anything about it" – Investor

"Smart is complex and rating is based on high uncertainty. Secondly, there is a lack of proven technology because the concept and its suppliers are new" – Property manager

"Not enough experience and knowledge about the alternatives. I would have preferred to only weigh the criteria" – Area developer

"As facility management we only want to focus on our need and translate them into requirements, and not focus on the alternatives. That is the role of someone else" – Facility manager

"Difficult because of a lack of knowledge" – User representative

Only the sustainability advisor and Technical property managers did not specifically mention the difficulty of rating the alternatives. The sustainability advisor recognized the method and its value. The technical property managers seemed to have sufficient knowledge about the smart systems related to their criteria.

The second feedback statement is the Lagrange curve. This is only applicable to the property manager, area developer, investor and facility manager. The property manager stated that he found it difficult to set the top, low and intermediate for the same reason as the rating. The others did not give any feedback on the Lagrange curve.

The last feedback statement is weighing the criteria. This step was perceived very positive. It was logical to all stakeholders that criteria differ in importance and that weights needed to be given. None of the stakeholders explicitly stated that this was difficult. An important note that was given by the property manager and facility manager was that they preferred to only weigh the criteria. This statement was discussed and the area developer, investor and user representative agreed. They felt that a distinction could be made in what should be done by the stakeholders and by the researcher. The overall attitude is that alternatives are too difficult and need to be assessed by an expert. Weighing the criteria could be done by the stakeholders. The property manager and area developer stated that the criteria should be specified by an expert and the sustainability advisor elaborated on this by stating that it could be specified using literature.

Interview 4: iteration

This interview was intended to allow adjustments of the input by the stakeholders. This seemed to be a very important step. In this interview the results were also presented. When the stakeholder was satisfied with the input, he/she was asked to give feedback on the model.

The property manager, investor and area developer stressed again that they see the value of using a more standardized model rather than the current model. Moreover, the area developer is interested to use the model for other buildings in the CBD.

Facility management was positive about the process as it could help them translate their problems and goals into criteria and constrains. They also stated that the rank list is valuable for future decision-making. They stated that the result would certainly help them in a dialogue with the property manager.

The other stakeholders reacted neutral/ slightly positive about the outcome. No negative reaction was given to the outcome.

The decision-maker stated that at the beginning of rating the alternatives he expected that Cisco would be the most preferred option. After the rank list was shown he reacted positively as he stated that the output generated was as expected. He did not explicitly stated his expectations beforehand. The decision-maker ought the list to be correct and will be taken into account for further discussion. A proposed next step is to perform a pilot study to test if the recommended system works as intended.

What is interesting is that the process is perceived negatively but the outcome more positively. It could be that despite the problems during the process a good projection of their preference is achieved. This relationship between the two is not discussed with the stakeholders and may be relevant for future research.

5.2 Evaluation of research success

The paper of Brown and Adams (2000) is concerned with evaluating the effectiveness of the project management discipline in delivering successful project outputs where successful outcomes are measured in terms of time, capital (cost) and quality. These three elements will be used to measure the successfulness of the research output.

Time

In theory a minimum timescale is desirable (Brown and Adams, 2000). The time for the research was fixed for 5 months. It was possible to set a planning for 5 months and execute the research within the set timescale. However looking back on the process and feedback of the stakeholders, the amount of information available was inadequate. Because the concept smart buildings is fairly new there was none too little experience about the subject. The alternatives are also unique and not fully tested so reference cases were limited. This made it very time consuming to provide complete information. Because this was not achieved within time, the stakeholders had to define their input with a limited amount of information. Winch (2010) describes this limitation as uncertainty (see figure 5.1). The definition of uncertainty is the difference between the amount of information available and the amount of information required to take a decision (Winch, 2010). Uncertainty negatively effects the input and therefor the output of the model.

The management of information is a process to reduce uncertainty over time (see figure 5.2). At the beginning of the process uncertainty is high. In order to reduce it, information is given. The level of uncertainty at a particular point in the project life cycle relative to earlier and later points in the project life cycle may be thought of as the level of dynamic uncertainty on the project (Winch, 2010). In this case, the reduction of uncertainty seemed not fully achieved and the amount of information possessed remained to low. More time would have been helpful to inform the stakeholders better about smart systems.

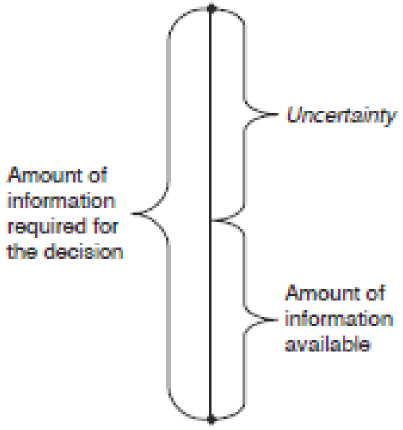


Figure 5.1 Uncertainty (Winch, 2010)

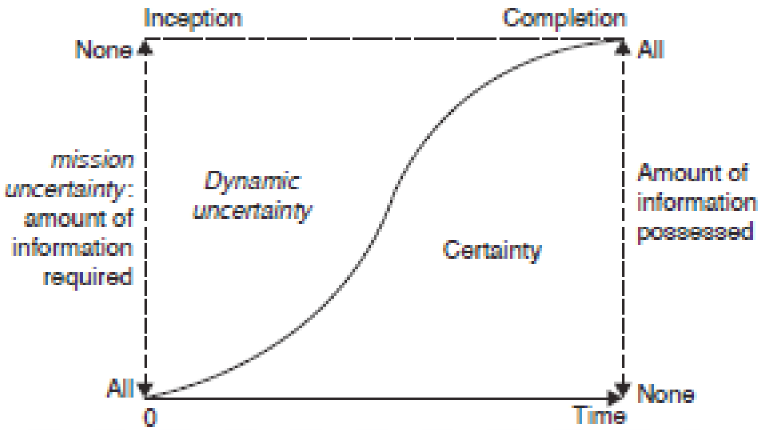


Figure 5.2 Dynamic uncertainty (Winch, 2010)

Capital

Capital can be divided into a number of different, and not completely substitutable, dimensions (Winch, 2010). The forms of capital are physical (such as costs), human, natural and social capital. The dimension that is relevant to this research is human capital. Human capital is held by people in the form of their skills and capabilities (Winch, 2012).

In the research the capabilities of the stakeholders are of great importance. Based on their capabilities the variables, weight and scores are established. They are the only source of input for the model. The output of the model is simply the projection of what would happen when the input variables occur in a real situation (Anderson, et al. 2016). Therefor the output depends on the human capital (the ability to give accurate input).

Based on the feedback and own observations the capabilities of the stakeholders were limited. There was clearly a lack of knowledge about smart systems. This made it hard to establish good input, which subsequently negatively effects the output.

Due to iteration the input could be altered and improved. Iteration was a crucial part of the process in order to improve the human capital. Iteration should progressively reduce uncertainty through time and increase certainty until all the information required for the project is available at completion and embodied in the input created (Winch, 2010). Iterations seemed to reduce uncertainty but not to the extent that all information required is available. It is hard to say to which extend iteration improved the knowledge of the stakeholders but it is assumed that it was the main factor in the uncertainty of the model.

Another factor of uncertainty is the capability of the researcher. The explanation of the research scope was done in the first interview. Later it became evident that some stakeholders interpreted the scope differently and therefor specified other variables. During the process the scope became more clear and with the use of iteration the variables could be adapted.

Quality

The last measurement is quality, which relates to the product. The product of this research is the model and its output. The model can be used independently of any other decision-making technique. The decision-maker is able to use the model to calculate the added value of different alternatives on a certain subject. The method, similar to the PAS approach (Arkesteijn et al., 2017) can be reproduced for any multi-criteria problem.

The output of the model is specifically oriented to the problem that is present in the case. Each case is unique so the ability to produce a unique set of variables, weight and preference scores is very valuable. The recommendation is tailor-made for the case. This greatly adds to the quality of the research.

Based on this short evaluation the success of the research can be summarized as follows: the tailor-made output is very valuable for the specific recommendation about the preferences of alternatives on a case. However due to a lack of stakeholder knowledge about smart systems and time limitations to inform adequately, the input, and therefor output, consists of uncertainty. It is not clear how much uncertainty is present but it should be taken into account when discussing the outcome.

5.3 Process of choosing the appropriate method

The process of choosing an appropriate research method is similar to the process that belongs to the research. It was an iterative process in which multiple methods and techniques are used, evaluated and sometimes dismissed (see figure 10.3). This chapter describes how I came to the final research approach.

Empirical vs. operational

The first question to ask is if the research should be empirical, operational or hybrid. The goal of empirical is understanding and is past-oriented. That of operational is improvement and is future-oriented (Binnekamp, 2014). The goal of SRE is to improve the SHG by finding the most preferred smart system to add value to the building. This is very much in line with operational research. A decision model is an appropriate tool that is common with this type of research. If the goal was to understand smart systems and to learn from it the question for the SHG case would be more like: what are the added values of smart systems in existing real estate? The case would then be a knowledge-related, descriptive and focussed on smart systems implemented in the past.

Operational research

Binnekamp (2014) elaborated on six common types of operational research. The goal to optimize added value relates to two types of operational research: optimization analysis and preference measurement. Added value is defined as the most preferred option and includes the subjective nature of the stakeholders. Preference measurement was concluded to be the appropriate method. The other types of research did not fit the problem and goal. If the problem, goal and research question was to be different, another method may be relevant. This is discussed below.

Regression analysis

Regression analysis is aimed at the development of a statistical model that can predict the values of a dependent variable (Binnekamp, 2014). Predictions are often based on rules of thumb derived from historic values, that is a regression analysis, of past projects (Binnekamp, 2014). The goal is similar to that of this research but plenty historical data should be available to execute the regression analysis. The research problem also implies a unique set of variables while regression analysis tries to find a prediction based on similar variables. Since there is little historical data, regression analysis is not possible. If historical data was to be present, the research question could be in the form of the following: How can regression analysis predict the added value of a smart system, based on similar projects?

Cost quality analysis

This type of analysis will only focus on the financial aspect of optimization problems. Determining whether or not an investment proposal is feasible is the main goal (Binnekamp, 2014). The goal of my research is to capture the entire added value of smart systems. The financial aspect is only a part of the added value. A research question suitable for cost quality analysis could be: how could a smart system positively effect the Net Present Value (NPV) of an investment?/ how could a decision model predict the NPV of a smart building?

Optimization analysis

The mathematical modeling technique of Linear Programming (LP) helps us find the optimal solution given an objective function and a set of constraints (Binnekamp, 2014). All variables are constraints and within the feasible field, the model tries to find the optimum based on a single objective, often a financial objective. The problem in my research implies that not only constraints are relevant but also the preference of stakeholders. The preference of stakeholders cannot be included in optimization analysis. Secondly, optimization analysis often focusses on multiple subjects, in this case multiple buildings (Binnekamp, 2014). If this was the case the research question related to optimization analysis could be: How can a decision model predict the optimum smart building portfolio based on a set of constraints?

Spatial allocation analysis

This method is concerned with the development of mathematical techniques and tools for negotiations on the spatial dimension of resources (Binnekamp, 2014). This type does not relate to the research problem described. The formulation of a relevant research question is as follows: which spatial layout of the resources fits the activities to be accommodated best, in accordance with stakeholders' wishes, goals, and constraints, and with the architectural style chosen (Binnekamp, 2014).

Network planning and mitigations

LP programming method based on the principles of construction planning to efficiently plan activities. This is also a method that falls out of the problem scope of the research. It focusses on effectively planning the entire problem-solving process, especially the implementation. A research question related to the implementation of a smart system could be: how can a mathematical model predict the optimum line of activities to implement a smart system?

PBD vs. PFM

Before the research, the research proposal recommended to use PBD because no alternatives were known beforehand and an endless amount of design options seemed possible. The PAS approach was a suitable method to conduct the research. However at an early phase of the research it became evident that the amount of alternatives was limited and to design a solution would possibly lead to a non-existing design. For that reason the switch from PBD to PFM is made (with the Lagrange technique still included).

After establishing the first sets of variables the Lagrange curve was questioned. The technique seemed unnecessary complex and therefor became a secondary technique. The main technique became the scaling of alternatives. After conducting the research the scaling of alternatives was also questioned. The scaling of alternatives was perceived to be difficult due to a lack of knowledge. Now the discussion is raised if the Lagrange curve would have been a better technique to mitigate this problem.

To decide between PBD and PFM depends on if the alternatives are known beforehand or not. The technique however, does not depend on this fact. In the research both the Lagrange curve and scaling of alternatives are used and are applicable in PFM and PBD. The research did not discuss any other scaling techniques, such as the Likert scale. Exploring other scaling techniques could give more insight in choosing an appropriate operational research technique.

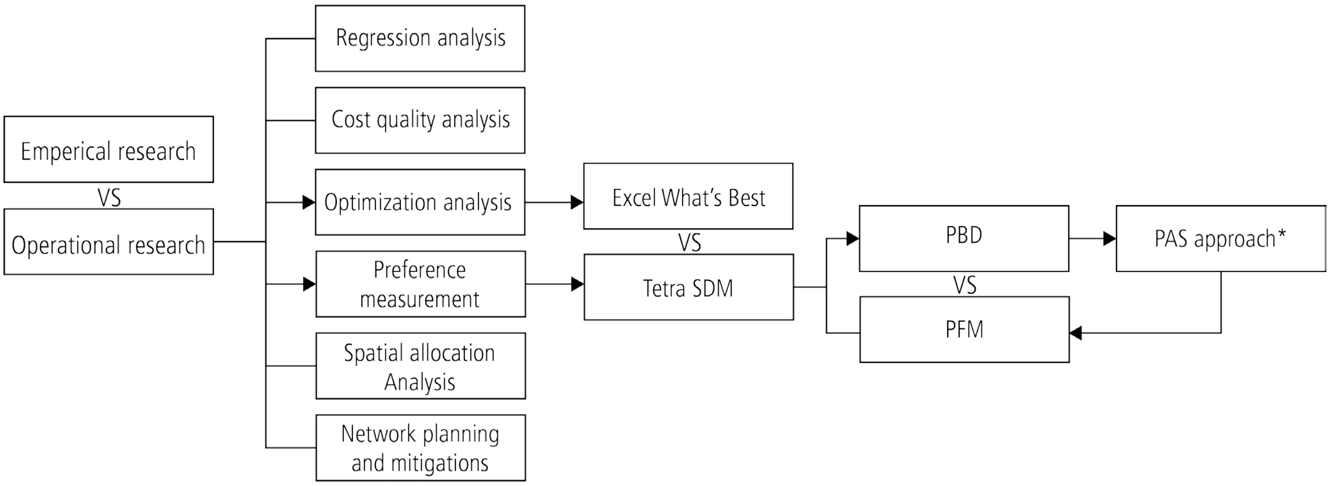


Figure 5.3 The research process

5.4 Lessons learned

The specific objective of the PAS approach was to generate and select alternatives to solve the problem of the TU Delft's food facilities. Food facilities were well known to the stakeholders and the stakeholders were very positive about establishing preference scores. Compared to the feedback and evaluation of my research the stakeholders were less positive. The main reason was a lack of knowledge about smart systems and insufficient time to improve the level of knowledge. Because the approach depends heavily on the input of the stakeholders, their knowledge is crucial for a successful project. Before applying the PAS approach (or similar approach) make sure human capital is sufficient and if not, consider enough time to improve human capital up to the a sufficient level.

Secondly, the process of providing the stakeholders with adequate knowledge and establishing all variables, weight and scores is intensive. This reduces the possibility to quickly produce and outcome and reproduce the approach. Several stakeholders mentioned that they see value in simplified version of the model, with more standardized elements.

The third lesson learned is to decide whether to use PFM or PBD. If the amount of alternatives is to large and it is too time-consuming to evaluate all of them, PBD is more appropriate and vice versa. However, choosing the appropriate scaling technique is flexible and depends on the nature of the case and its stakeholders.

5.5 Proposed alternative model

Based on the lessons learned an alternative model is presented. This chapter contains a recommendation how to develop a different model with a similar objective; finding the best decision. The proposed model is an expert tool, leaving the stakeholder out of the elements in which they supposedly lack knowledge. Secondly, the model is more standardized and has the purpose to be quickly used and reused. This could lower the threshold of using the model.

The element that was most difficult for the stakeholders was the preference scores and therefor it is chosen to standardize the variables, alternatives and scores. Only the weights are based on the input of the stakeholders.

Note that this model is in concept phase and has not yet been tested. The explanation is brief and does need more research in order to assess its value.

1. Generic decision model

The generic decision model consists of alternatives, criteria and scores. However, the alternatives, criteria and scores are filled in by an expert and are fixed. The only reason to adapt these variables is if an alternative changes or a new alternative needs to be added.

1.1. Define Alternatives

If the amount of design alternatives is limited all relevant alternatives can be predefined and the same alternatives can be re-evaluated in a different case with a similar scope. The scope of the model is determined, in this case it is indoor positioning.

1.2. Define constraints

The constraints are fixed, based on theory, and are the most frequent and essential criteria for every decision making process focused on indoor positioning smart systems. For example, the requirements of Mautz (2012) could be a variable selection. The constraints have to be filled in based on the case and determine which of the alternatives are feasibility for the case. This is done by the expert.

1.3. Define Criteria

Similar to the constraints the criteria are fixed, based on theory. Because variables can be seen as both a constraint and criteria there may be a lot of overlap. Take for example costs. The maximum budget may be €100.000, however a system costing €70.000 may be valued lower than a system costing €50.000.

1.4. Define Score

The alternatives and criteria are both fixed in the model. Because in the research the stakeholders stated that they did not have enough knowledge to effectively score the alternatives, the alternatives are in this case scored an expert. This means that the overall score is not based on the preference of stakeholders but merely of the knowledge and experience of the expert.

The process of establishing the alternatives, criteria and scores is assumed to be time-consuming the first time. However because these variables are fixed (except when a supplier changes its product), using the model will require a shorter process.

2. Select stakeholders

All interested stakeholders need to be selected.

3. Assign weight

The only input necessary from the stakeholders is the weight, in order to include the perception of the stakeholder. Two options exists. The stakeholders are invited in a collective meeting to establish the weight of all predefined criteria or each stakeholder rates all predefined criteria. The latter option also requires giving weight to the stakeholders, which could be done by the decision maker, the stakeholders or the researcher. If a criterion is not of interest to the stakeholder it simply rates it a weight of 0%.

4. Rank list

The formulas used in the standardized model are identical as the research model. Therefor the rank list is calculated in the same way. Note that the score is not an overall preference score but a combination score of preference in the form of weight and expert input.

5. Combine alternatives

Combining the alternatives is identical as the research model.

6. Iteration

The iteration process focusses only on the assigning of the weights. Within this process the stakeholder can view the results and discuss his/her weights related to the scores. Based on this insight information it is possible to adapt the weight until satisfied.

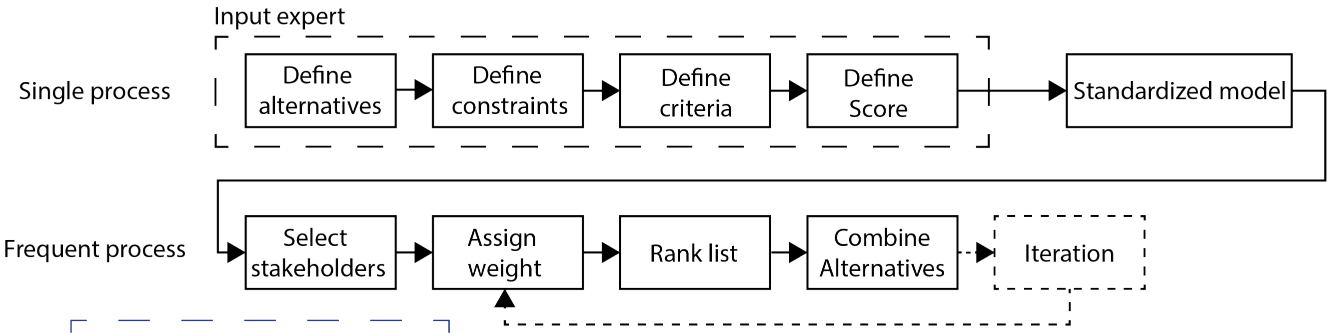


Figure 5.4. Alternative model

5.5.1 Advantages

Note that the model is not yet tested so the (dis)advantages are assumed.

The purpose of the alternative model is to simplify compared to the original research model and PAS approach. Two main advantages are pursued: (re)usability and expert knowledge.

The model may be of higher value when it can be used and reused quick and easy. The use of the original decision model takes time and effort. If a company is in the initiating phase it may not desire to put much time and effort in a preliminary assessment. A minimum time and effort decision model has a lower threshold to be used. The output can be quickly produced and used for further discussion in the initiating phase.

The second advantage is based on the fact that stakeholders may lack knowledge. If so, an expert may provide better judgement in specifying criteria and scores. The expert is able to talk extensively with suppliers and other experts in order to establish reliable scores. The stakeholders often do not have the possibility or willingness to go through this process. Moreover, if every stakeholder in each case has to go through this process it is very time consuming. Therefor the expert establishes all knowledge once and updates only if necessary.

The model itself may have financial value as well. The model may be sold to other interested parties in the form of consult or use of the model. The investing party does not need to invest time and effort in understanding the alternatives but let the expert take care of this.

5.5.2 Disadvantages

The standardization of the PFM research model brings complications as well. The main disadvantage is subjectivity. This research clearly shows that both quantitative (e.g. costs) and qualitative (e.g. satisfaction) variables are of interest to the stakeholders. An expert may be able to standardize the quantitative variables. For example, it is common knowledge that a more expensive alternative is scored lower than an cheaper alternative. This criterion can be calculated based on a linear formula. However, a variable such as satisfaction completely depends on the preference of a person. Preference is not a physical property of the objects being valued, that is, preference is a subjective, i.e. psychological, property (Barzilia, 2009). This means that an expert cannot define the score of an subjective variable.

Even so, quantitative variables also include some subjectivity. The accuracy of an indoor positioning system is at first objective. Take for example the following situation:

There are three systems, A, B and C, with a positioning accuracy of 1, 3 and 26 meter respectively. It is assumed that the lower the accuracy is in meters, the higher the accuracy is and the higher the score. Based on linear expert scoring system C will get a score of 0, System A a score of 100 and System B a score of 92. The score (92) of system B was calculated based on the linear line between the points of system A and C. However a stakeholder may be almost evenly satisfied with an accuracy of 1 and 3 meter as it is still able to easily find the person. However, he is less satisfied with 26 meters as it gives him some trouble finding the person. The stakeholder would rate the system A, B and C, 100, 98, 0 respectively.

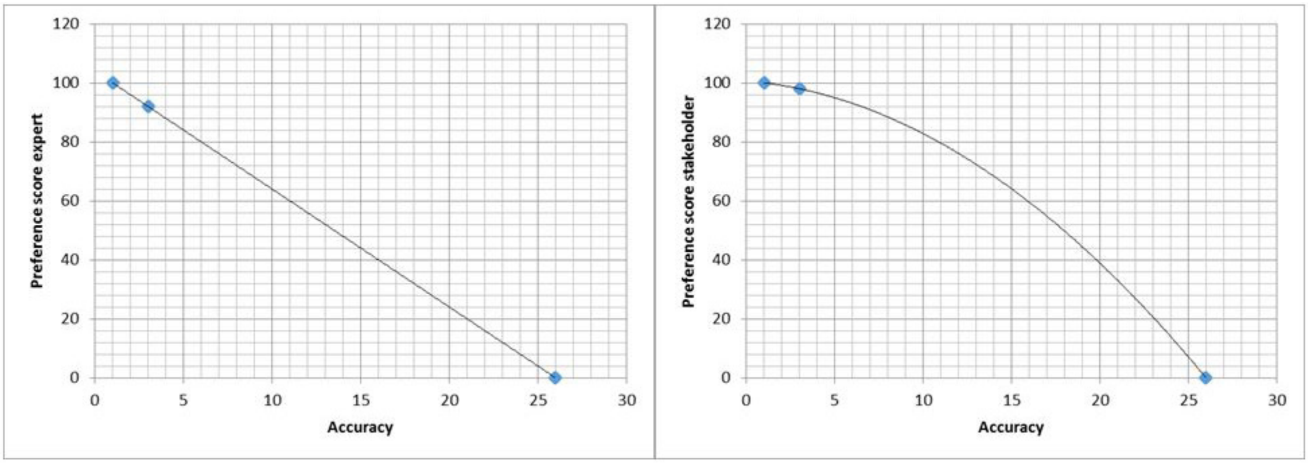


Figure 5.5 Linear score by expert (left) and preference curve by stakeholder (right)

This example shows that there is a difference in score between the expert rating and stakeholder rating. This means that even with quantitative measures the subjectivity of the expert is present. The expert assumed a linear relationship between the accuracy in meters and the preference score. However the relationship could in reality be an curve, S-curve or any other mathematical formula. In order to reproduce reality the mathematical formula must represent the specific situation (Anderson, 2016). In the alternative model this is limited.

5.5.3 Short study of the alternative model

To experience the difference between the alternative and research model, the alternative model is also tested. Due to time limitations the alternative model is tested on two stakeholders, both weighing 50%. Secondly, the standardized model is filled in by another expert. The purpose of this process is to see if the experts would rate the alternatives differently.

Expert rating process

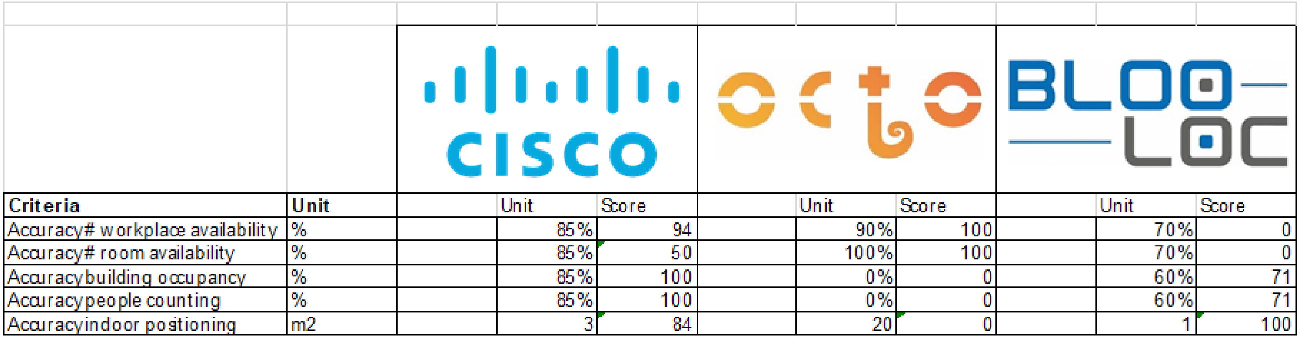
For the expert rating process an external expert is asked to fill in the standardized model. According to the assumed disadvantage (see above) there may be differences in the rating scores due to subjectivity. However because the criteria are all quantitative the difference is expected to be small.

Valks, a researcher at the Delft University of Technology, is currently writing his PhD on smart campus tools and has sufficient knowledge about the smart system alternatives. Moreover, he is familiar with PFM and the PAS approach.

After conducting the process of rating the alternatives, the subjectivity problem became very clear. Criteria were interpreted differently and for one criterion the unit was also changed.

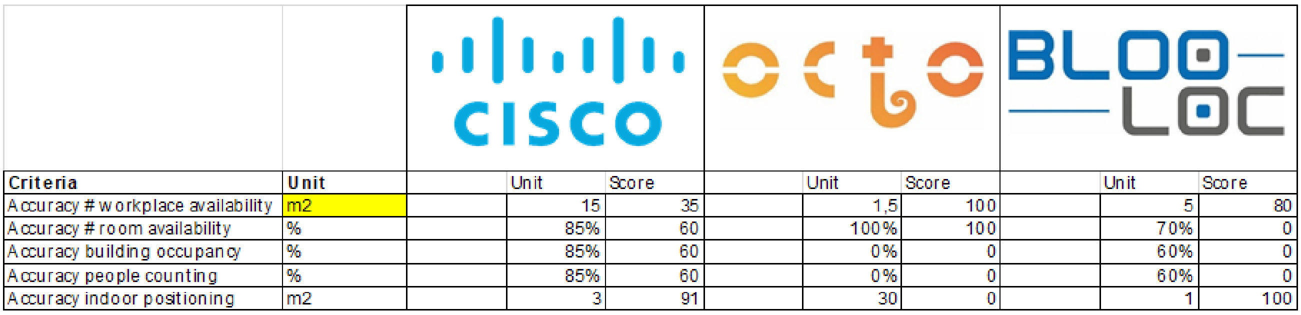
At first the unit values (e.g. 85% accuracy) remained the same. Valks used for each criterion the Lagrange curve and did not establish a linear formula but established a curve based on the characteristics of the criterion. Based on the curves he established different scores for all fields (see figure 10.6 top and middle input).

Secondly, Valks interpreted the criteria different and established different unit values for the alternatives. This increased the deviation even further (see bottom of figure 5.6). The two expert inputs compared shows great differences and one criterion could not be compared anymore because of a different unit.



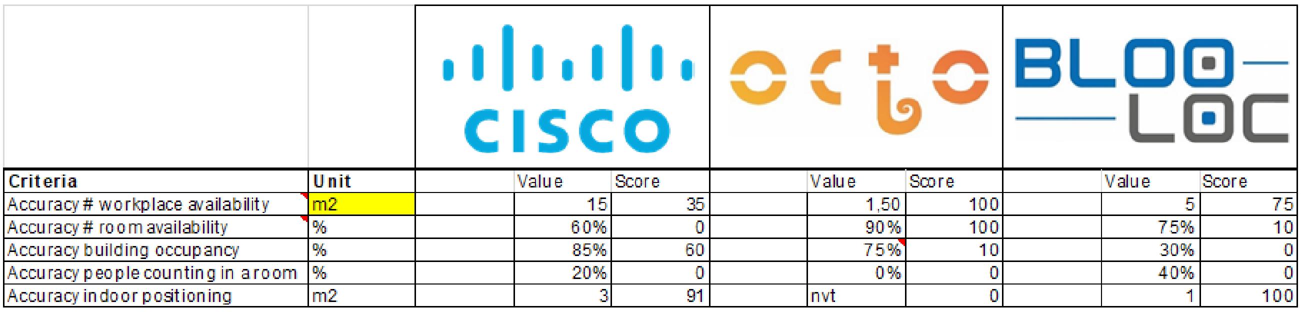
		CISCO			octo			BLOO LOC		
Criteria	Unit		Unit	Score		Unit	Score		Unit	Score
Accuracy# workplace availability	%		85%	94		90%	100		70%	0
Accuracy# room availability	%		85%	50		100%	100		70%	0
Accuracy building occupancy	%		85%	100		0%	0		60%	71
Accuracy people counting	%		85%	100		0%	0		60%	71
Accuracy indoor positioning	m2		3	84		20	0		1	100

Expert input: Author



		CISCO			octo			BLOO LOC		
Criteria	Unit		Unit	Score		Unit	Score		Unit	Score
Accuracy # workplace availability	m2		15	35		1,5	100		5	80
Accuracy # room availability	%		85%	60		100%	100		70%	0
Accuracy building occupancy	%		85%	60		0%	0		60%	0
Accuracy people counting	%		85%	60		0%	0		60%	0
Accuracy indoor positioning	m2		3	91		30	0		1	100

Expert input: Values by Author, score by Valks



		CISCO			octo			BLOO LOC		
Criteria	Unit		Value	Score		Value	Score		Value	Score
Accuracy # workplace availability	m2		15	35		1,50	100		5	75
Accuracy # room availability	%		60%	0		90%	100		75%	10
Accuracy building occupancy	%		85%	60		75%	10		30%	0
Accuracy people counting in a room	%		20%	0		0%	0		40%	0
Accuracy indoor positioning	m2		3	91		nvt	0		1	100

Expert input: Valks

Figure 5.6 study of the alternative model

If you look closely to the scores between the first two excel sheets there are already tremendous differences. The reason for this is that both experts interpreted the relationship between alternatives and scores differently. The author formulated the scores by establishing a linear line. The most preferred alternative would get a score of 100, the least preferred alternative a score of 0 and the score of the third alternative could be find on the linear line between the most and least preferred alternative. Valks formulated a LaGrange curve and established a value for what he thinks would get a score of 100 and a score of 0. He also established an intermediate to create a preference curve. Because of different reasoning of both experts the scores of the alternatives are very much different. In the figure below both preference formula's for the criterion "accuracy building occupancy" are shown. This figures illustrates the subjectivity of the expert and how they differentiate from each other. The subjectivity relates to the expert and is fixed. It limits the ability to project a specific situation and proves the disadvantage discussed above.

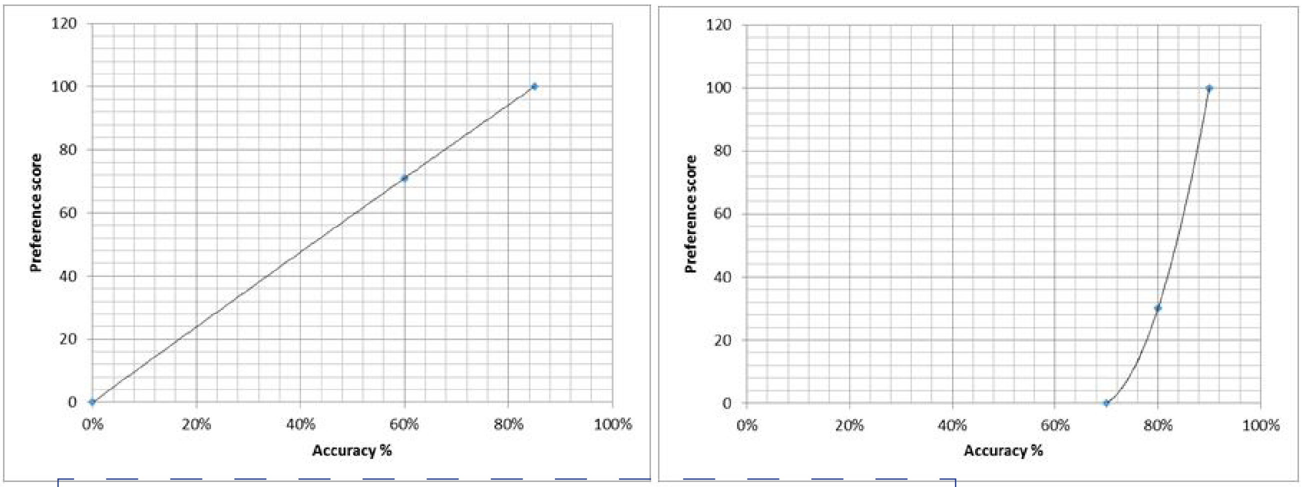
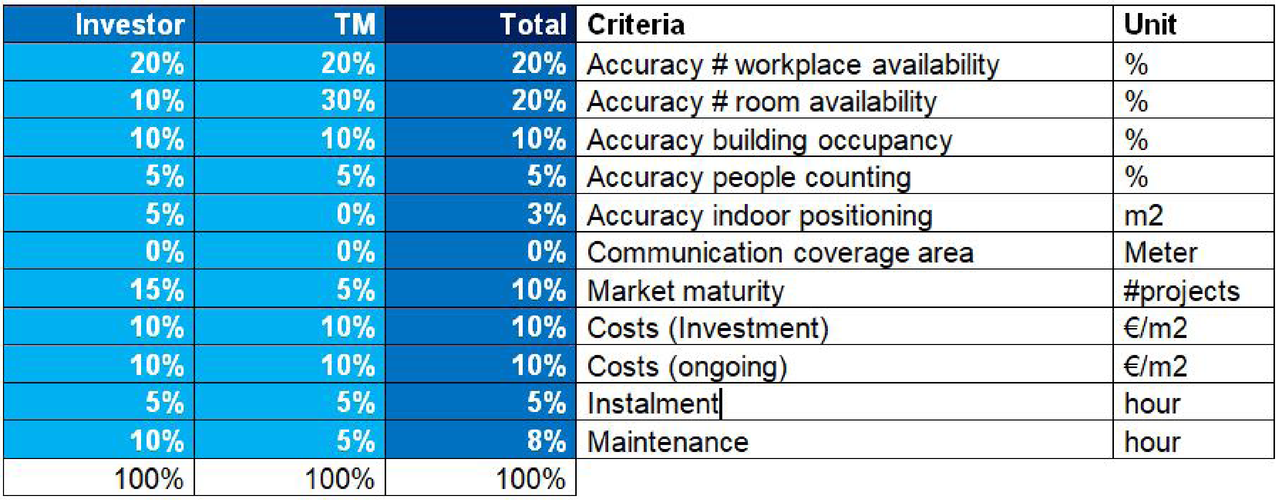


Figure 5.7 Left: preference curve Author. Right: preference curve Valks.

Stakeholder process of the alternative model

The rating of alternatives was perceived difficult by, among others, the tenant manager and investor. They both stated that the rating of alternatives should be done by an expert and only the process of weighing the criteria could be done effectively by the stakeholders. The alternative model is tested by the investor and tenant manager in order to evaluate their feedback.

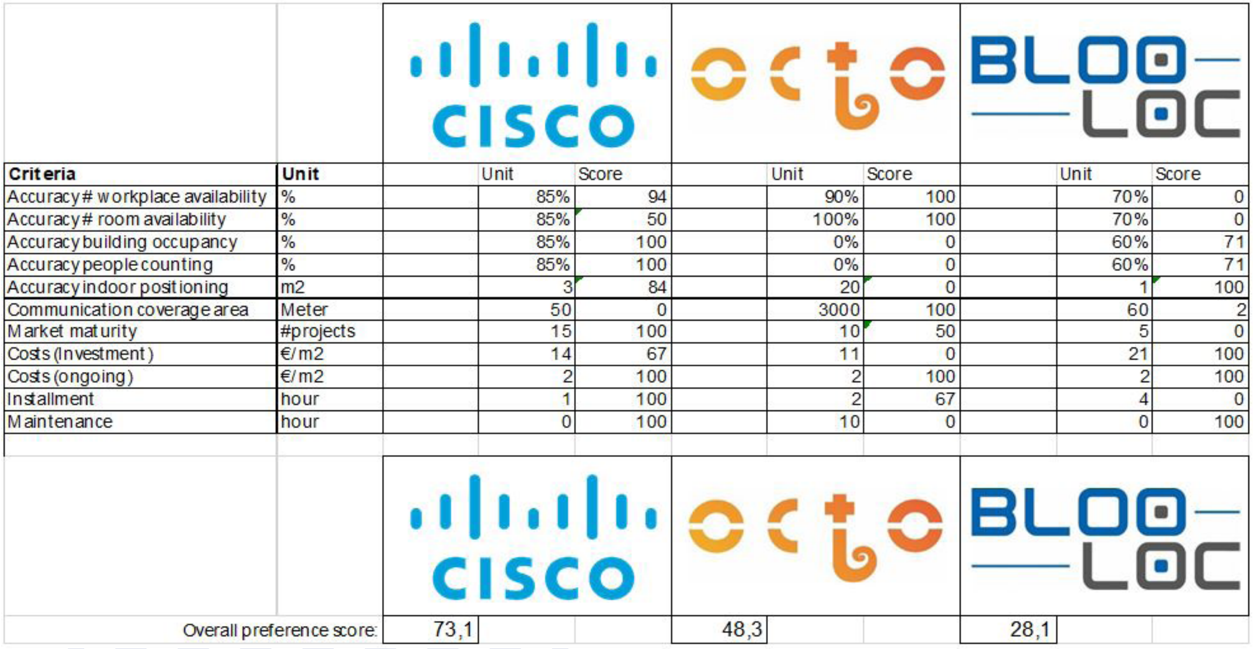
The stakeholder process of the standardized model was very short in comparison with the research model. Both stakeholders were able to fill in the weight of all criteria within the hour (see figure 5.8). It was decided that both stakeholders have the same weight. The total weight is the average of the weight of both stakeholders.



Investor	TM	Total	Criteria	Unit
20%	20%	20%	Accuracy # workplace availability	%
10%	30%	20%	Accuracy # room availability	%
10%	10%	10%	Accuracy building occupancy	%
5%	5%	5%	Accuracy people counting	%
5%	0%	3%	Accuracy indoor positioning	m2
0%	0%	0%	Communication coverage area	Meter
15%	5%	10%	Market maturity	#projects
10%	10%	10%	Costs (Investment)	€/m2
10%	10%	10%	Costs (ongoing)	€/m2
5%	5%	5%	Instalment	hour
10%	5%	8%	Maintenance	hour
100%	100%	100%		

Figure 5.8. Criteria weight

Based on the predefined scores by the expert and the input of the stakeholders the overall preference score can be calculated (see figure 5.9). The stakeholders stated that there was no need for iteration and the outcome is final.



		CISCO			octo			BLOO LOC		
Criteria	**Unit**		Unit	Score		Unit	Score		Unit	Score
Accuracy # workplace availability	%		85%	94		90%	100		70%	0
Accuracy # room availability	%		85%	50		100%	100		70%	0
Accuracy building occupancy	%		85%	100		0%	0		60%	71
Accuracy people counting	%		85%	100		0%	0		60%	71
Accuracy indoor positioning	m2		3	84		20	0		1	100
Communication coverage area	Meter		50	0		3000	100		60	2
Market maturity	#projects		15	100		10	50		5	0
Costs (Investment)	€/m2		14	67		11	0		21	100
Costs (ongoing)	€/m2		2	100		2	100		2	100
Installment	hour		1	100		2	67		4	0
Maintenance	hour		0	100		10	0		0	100
		CISCO			octo			BLOO LOC		
	Overall preference score:	73,1			48,3			28,1		

Figure 5.9. Results standardized model

The process was perceived positive by both stakeholders. It was simple and the criteria were easy to understand and weigh. The question was asked if the stakeholders felt all criteria are present. The investor explained that the criteria all focus on the product and are in that aspect complete. Based on these criteria he could rate the alternatives according to his interest.

For example, for the main research model the investor defined the criterion usability. This is a very qualitative criterion and could not be included in the standardized model. However based on the criteria present the investor was able to take usability into account. He did this by looking at the accuracy of the product. If accuracy is good, this would positively affect usability.

The test with the investor and tenant manager shows that for some stakeholders the standardized process is better. It excludes stakeholder knowledge about difficult aspects such as smart systems and provides a more simple and time-efficient procedure for the stakeholder. Note that the stakeholders did not question the quality of the predefined scores.

The difference between the two models is a trade-off between customization vs. investment of time and effort. If low investment is preferred, the output will be less customized and vice versa. Secondly, the two models are also a trade-off in knowledge required and available. If the knowledge available is low and difficult to improve the preference for an expert tool may be higher and vice versa.

5.6 Problem analysis comparison

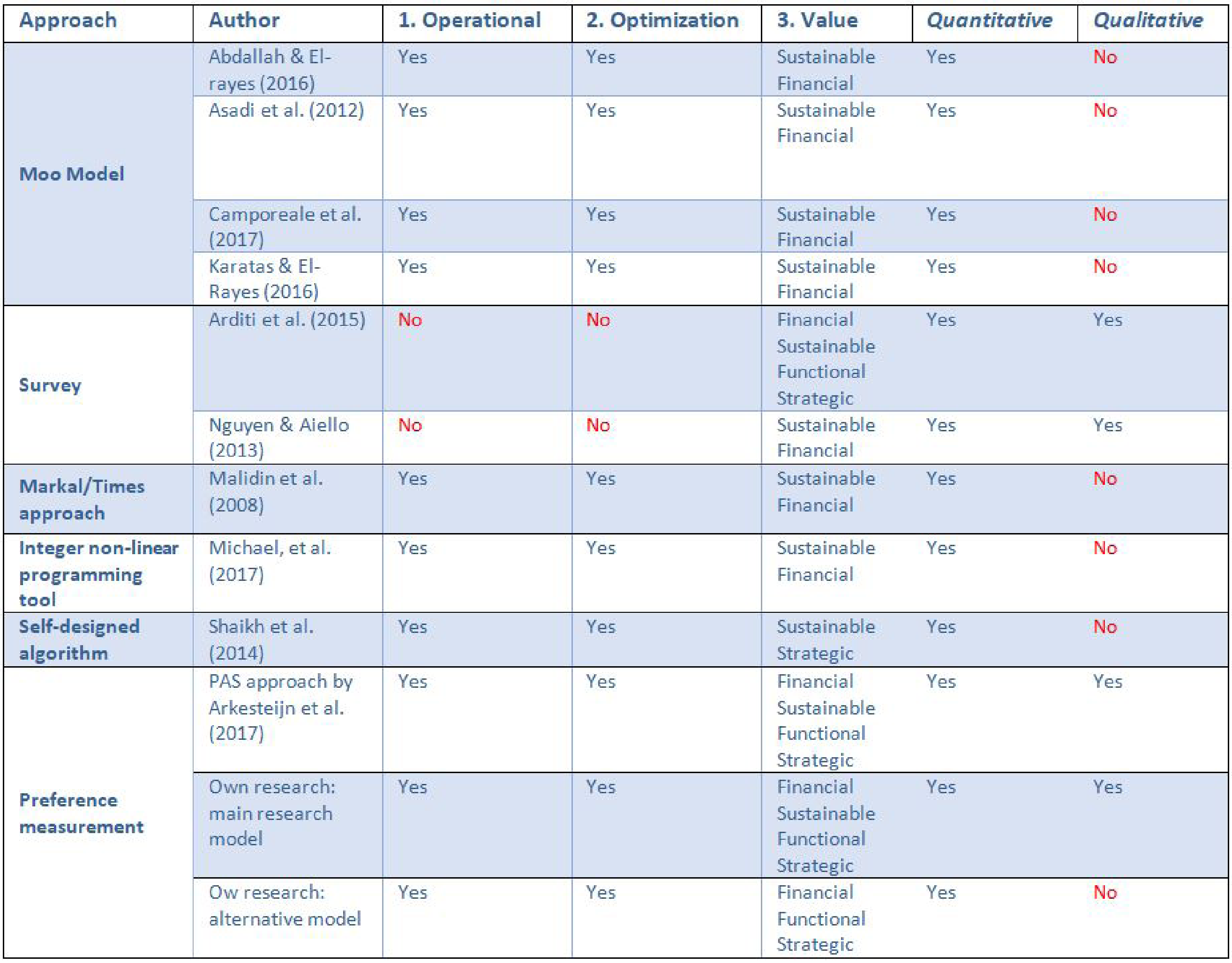
In the beginning of the research the following was stated:

"Previous research provides models that are capable of predicting the optimized value for conflicting quantitative values but fail to incorporate qualitative values".

In this paragraph the main research model is compared to the papers that are analysed during the formulation of the problem statement (see figure 5.10). The comparison is done to show how the research model solves the limitations of the previous research papers.

During the problem analysis it became evident that previous research provided several mathematical decision model (Moo model, Markal/Times approach, Integer non-linear programming tool and self-designed algorithm). These models only included two or three quantitative criteria. The author defined these criteria beforehand and are fixed in the model. It is not possible to include more criteria. Moreover, it is not possible to include qualitative criteria. The PAS approach (Arkesteijn et al., 2017) and the main research model do not have this limitation. The models are capable of including an endless amount of criteria and include both quantitative and qualitative criteria. The qualitative criteria are translated for a mathematical model by going through the process of giving preference scores and weights. These are the parameters of the mathematical model that represent both quantitative and qualitative criteria.

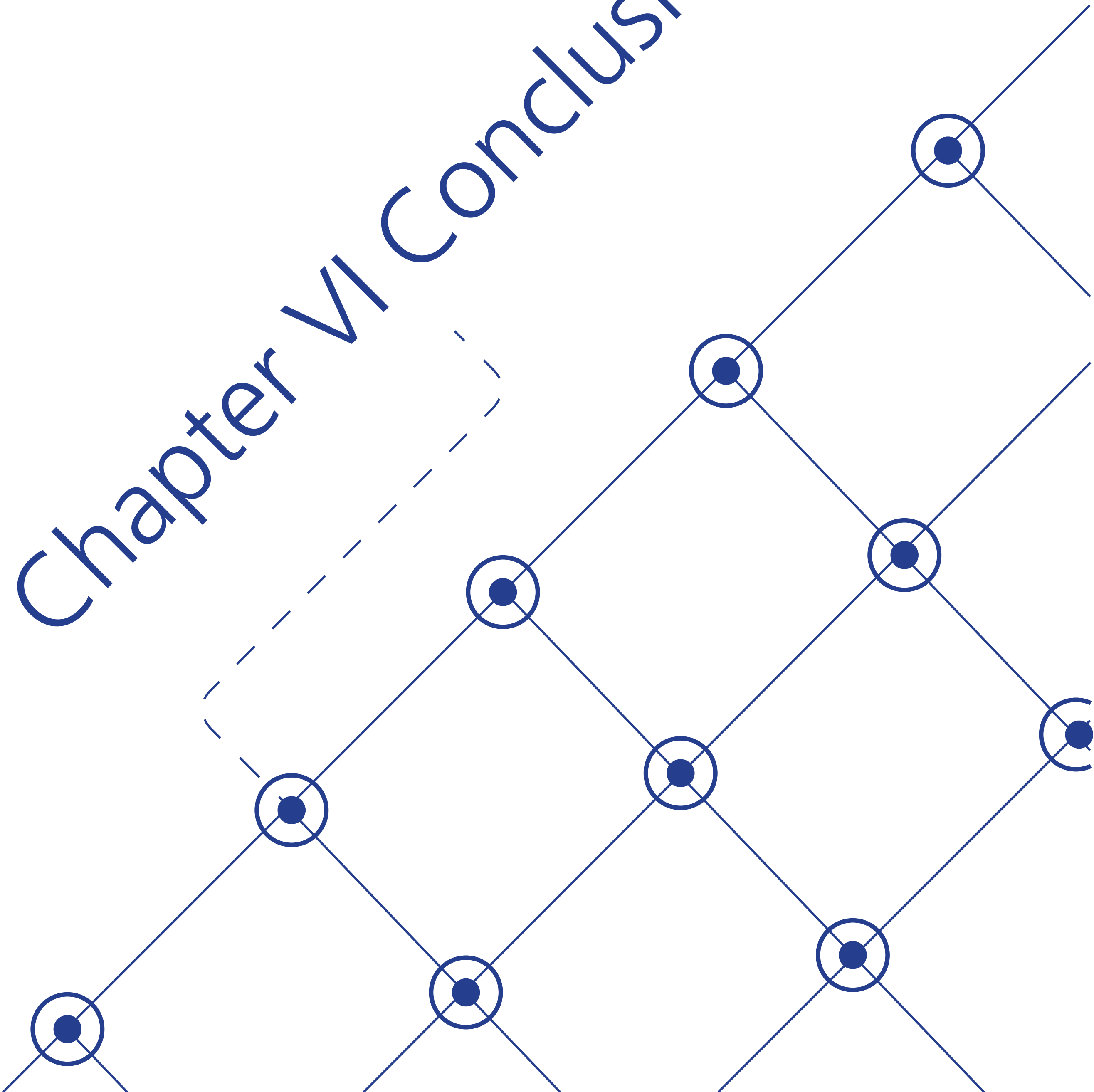
Abdallah & El-rayes (2016), Asadi et al. (2012), Camporeale et al. (2017), Karatas & El-Rayes (2016), Malidin et al. (2008), Michael, et al. (2017) and Shaikh et al. (2014) are only operational. Arditi et al. (2015) and Nguyen & Aiello (2013) are only empirical. The operational research papers provide a decision model but excluded qualitative criteria. The empirical research papers include both quantitative and qualitative criteria but exclude a decision model. Own research and the PAS approach (Arkesteijn et al., 2017) are mainly operational but include an empirical element. Empirical research in order to establish - quantitative and qualitative - input from the stakeholders and operational research for the development of the model and calculation of the overall preference scores. The combination of both methods allow the researcher to overcome the limitations that occur in the other papers.



Approach	Author	1. Operational	2. Optimization	3. Value	*Quantitative*	*Qualitative*
Moo Model	Abdallah & El-rayes (2016)	Yes	Yes	Sustainable Financial	Yes	No
	Asadi et al. (2012)	Yes	Yes	Sustainable Financial	Yes	No
	Camporeale et al. (2017)	Yes	Yes	Sustainable Financial	Yes	No
	Karatas & El-Rayes (2016)	Yes	Yes	Sustainable Financial	Yes	No
Survey	Arditi et al. (2015)	No	No	Financial Sustainable Functional Strategic	Yes	Yes
	Nguyen & Aiello (2013)	No	No	Sustainable Financial	Yes	Yes
Markal/Times approach	Malidin et al. (2008)	Yes	Yes	Sustainable Financial	Yes	No
Integer non-linear programming tool	Michael, et al. (2017)	Yes	Yes	Sustainable Financial	Yes	No
Self-designed algorithm	Shaikh et al. (2014)	Yes	Yes	Sustainable Strategic	Yes	No
Preference measurement	PAS approach by Arkesteijn et al. (2017)	Yes	Yes	Financial Sustainable Functional Strategic	Yes	Yes
	Own research: main research model	Yes	Yes	Financial Sustainable Functional Strategic	Yes	Yes
	Ow research: alternative model	Yes	Yes	Financial Functional Strategic	Yes	No

Figure 5.10. Research model compared to the analyzed models

Chapter VI Conclusion



6 Conclusion

This chapter describes the conclusion that can be drawn from the research. This is done by answering the main research question and sub questions.

6.1 Answering the sub-questions

The research consists of a demand and supply side, with the variables representing the demand and the alternatives the supply. The research question is divided into two sub-questions, each focusing on either the demand or supply. The sub-questions are:

1. Demand: Which parameters need to be represent in the decision-model to express the demand of the stakeholders
2. Supply: Which relevant design alternatives can be made based on existing smart technologies?

6.1.1 Demand

The demand is to add value to the building. The decision will be made based on the alternative that adds most value, or in other words, prefer the most (Arkesteijn et al., 2017). The following quote is used to define the demand:

"We note that to decide is to choose. We choose the alternative that we prefer, and prefer the alternative that adds value. This means that value can be measured by measuring preference, that is, evaluating/judging the alternatives as to the value they add, and in this context, value and preference are equivalent" (Arkesteijn et al. ,2017: p.244)

So to formulate the demand, the preference of the stakeholders can be used. A method within operational research that includes measuring the preference of the stakeholders is Preference Function Modelling.

Preference Function Modelling is a method that enables one to apply mathematical analysis and calculations to quantitative and qualitative demands of stakeholders. It allows stakeholders to determine their own input and translate it into mathematical values using several techniques. Two of those techniques are being used in the research: the operation of scale values and the Lagrange curve. Both techniques require three elements: variables, weight and preference scores. Based on these parameters the demand of the stakeholders can be expressed.

Variables

Variables are expressed by the stakeholders and are the points of interest relevant to the subject. The variables are further defined into constraints, criteria or both. The constraints are the feasibility restrictions with regard to maximum and minimum values to which the alternative needs to comply (Binnekamp, 2010). The criteria contain the value scales, with identical mathematical boundaries, which represent the preference of the stakeholder.

Preference score

The variables are evaluated using PFM's algorithm, which enables finding the alternative that is both feasible and most preferred by all decision makers as a group (Binnekamp, 2014). In order to do so, the stakeholder has to rate each criterion within the boundaries, either by the operation of scale values or the Lagrange curve.

The operation of scale values is an evaluation method in which all feasible alternatives are presented to the stakeholder. The stakeholder is asked to rate his most preferred alternative 100, the least preferred 0 and the rest in between.

The Lagrange curve is a design or evaluation method in which the stakeholder is asked which value would be getting a score of 100 and which a score of 0. The stakeholder is than either asked what score the intermediate value would get. This would result in three coordinates in which a curve can be fitted. The curve is constructed using a Lagrange curve, which interpolates between the given number of polynomials. The curve represents the preference and for each value the preference can found. The formula used for this method is:

$$P(x) = ((x - x1)(x - x2)/(x0 - x1)(x0 - x2)) * y0 + ((x - x0)(x - x2)/(x1 - x0)(x1 - x2)) * y1 + ((x - x0)(x - x1)/(x2 - x0)(x2 - x1)) * y2\ldots$$

These techniques can both be used to translate subjective criteria into mathematical values (scores). The operation of scale values can be used best when the amount of alternatives is limited and it is not likely that changes will occur. The Lagrange curve can be used best when the criterion is objective (e.g. costs), the amount of alternatives is unknown or when changes in value are likely to happen.

Weight

The relative importance of criteria and stakeholders are incorporated using weights. The overall preference rating of an alternative is then determined by an algorithm that takes each alternative's preference rating on each criterion and its weight into account (Binnekamp, 2010). Weight is a necessary parameter in order to project a true situation. In reality, the importance of criteria varies and weight is a mathematical expression to project the variation in importance.

Secondly, the importance of the stakeholders is taken into account. The same principle applies to stakeholders as to criteria: there is a variation in importance between the stakeholders. Assigning the weights to the stakeholders can be done in different ways. By the decision-maker, researcher or the stakeholders.

6.1.2 Supply

The supply consists of the alternatives, in this case indoor positioning smart systems. The alternatives all fit the indented purpose (are feasible) but all being completely different. The amount of feasible alternatives is important for the applicability of this research. The principle of PFM is that the alternatives are known a priori. If not, this method is not possible and the PAS approach could be used, which is PBD.

So to answer the question, which relevant design alternatives can be made on existing smart technologies? This is case specific and depends on the scope. If the amount of alternatives is extensive, PBD (e.g. PAS approach) is more suitable and the supply will be designed in the course of the process. If the amount of alternatives is limited, the PFM (e.g. this research) is suitable and the supply will be selected beforehand. In this case, the scope was indoor positioning, the alternatives were known beforehand and the amount of alternatives was relatively low. Based on market research and collaboration with suppliers, eight design alternatives were selected that fit the intended purpose: bGrid, Blooloc, Brickstream, Cisco, iotspot, Lone rooftop, Octo and Philips.

6.2 Answering the main question

The main research question is: How can a decision model predict the added value of a smart system?

The answer to the research question will be, strategical, practical and technical. The strategic answer focusses on the process; how the decision model is created and how the prediction of the added value comes about. The practical answer focusses on the product (the mathematical model); did the model work in this case and how can it be used in other cases. The technical answer will focus on the alternatives; which alternatives are there to be considered and how does each system work.

Strategic: process

Preference Function Modelling, based on the PAS approach worked as intended. The method consists of a procedure, structure and model. The procedure is a list of all the steps that need to be taken to come to an outcome. The structure describes the stakeholders that are involved and what they should do in order to come to a decision. Together they should supply all data necessary for the decision model to predict the added value of a smart system.

The procedure and structure can be summarized in a flowchart. The flowchart explains the process to answer the main research question. The procedure of the research is fixed. All steps (except step 8) need to be taken in order to achieve an output:

1. Select stakeholders
2. Define variables
3. Define constraints and criteria
4. Assign weight
5. Select alternatives
6. Rate the alternatives
7. Establish rank list
8. Combine alternatives
9. Iteration

The procedure explicitly explains what needs to be done to continue to the next step. Step 4 (assign weights) does not necessarily need to be done before step 6. It may be postponed to after step 6, as is done in the research. Step 8 is optional.

The procedure explains what needs to be done to derive to an answer but does not explain how. The structure explains how. The structure does not contain a step-by-step plan and may shorter or longer depending on the subject, timeframe and iteration process. The main activity of the structure is interviews. The interviews are necessary to establish the input (variables, constrains, criteria, weight and preference scores). Other activities are meetings with suppliers in order to establish the alternatives and building the model accordingly.

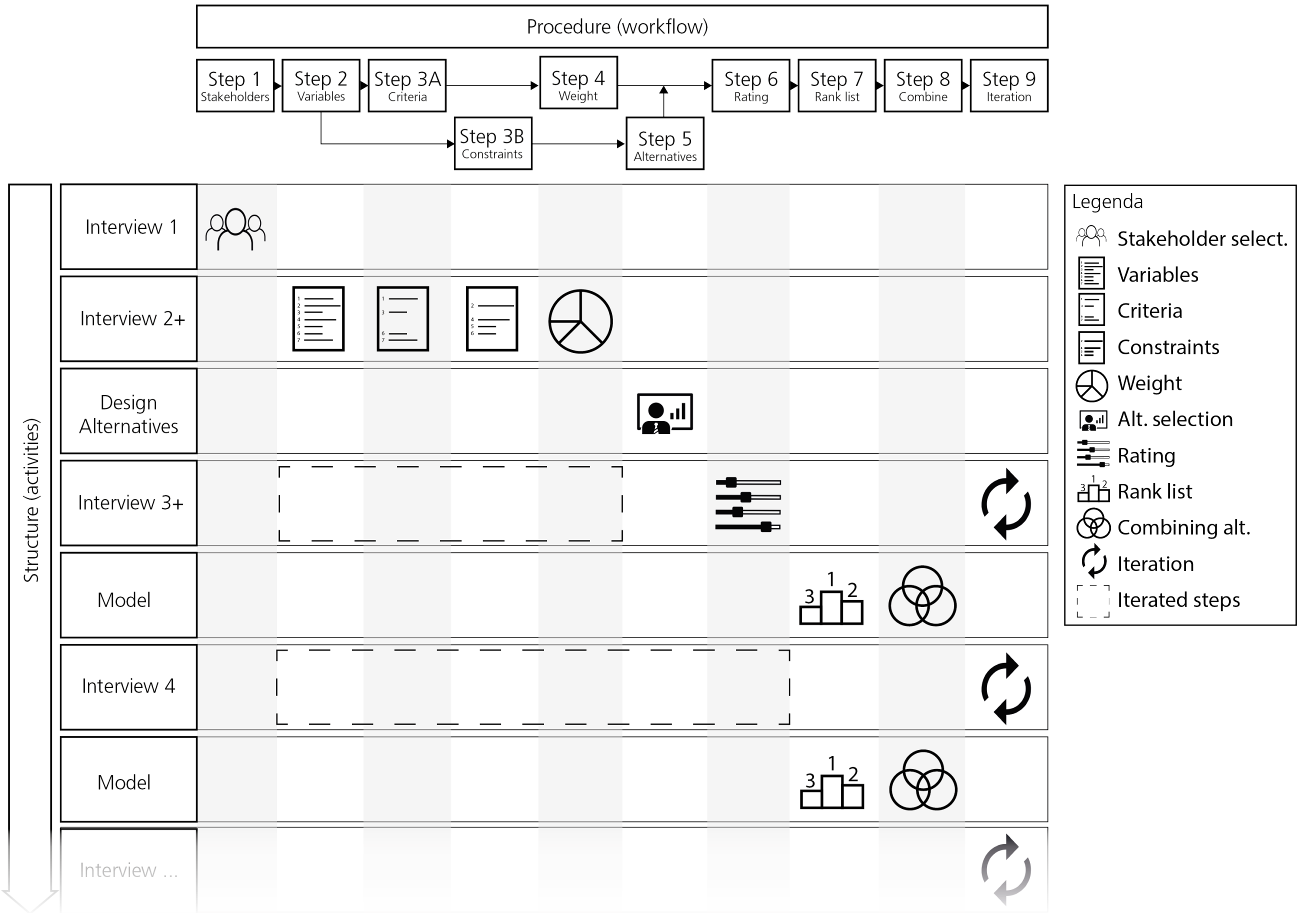


Figure 6.1 Flowchart

Interview 1 is acquaintance with different roles in order to select the interested stakeholders.

Interview 2 is to establish the variables, divide them into constraints and criteria and assign weights to the criteria. This may be done in single or multiple interviews. The assigning of weights may even be postponed and done after the preference scores are established.

Interview 3 is to give the preference score to each alternative on each criterion. The interview may also be used to revise previous steps. If weighing the alternatives is postponed it could be done in this set of interviews.

Interview 4 is established to revise all given input. During the process the stakeholders acquired new information and iteration makes it possible for the stakeholders to formulate their input as they intent. The use of such a learning process in the context of work practise and problem solving is described as reflection in action (Arkesteijn et al., 2017 and Schön, 1987).

Practical: product

The mathematical model successfully predicted the added value of smart systems. The added value is based on the input of the stakeholders. The throughput is an algorithm that takes all this input into account. The algorithm gives the output, which is the overall preference, score (see figure 6.2). The highest overall preference score is the most preferred model, in other words, adds the most value. The decision model is created in Excel and is designed according to the input given.

The model and the output is specifically oriented to the problem that is present in the case. Each case is unique so the ability to produce a unique set of variables, weight and preference scores is necessary to project a real situation. The recommendation is custom-made for the case. This greatly adds to the quality of the research method.

However, for a model to project a true situation not only the input variables should be case-specific, the translation from variables to mathematical values should also be according to the true situation. In order to project a true situation, the stakeholders need to have sufficient knowledge about the variables and alternatives. If not, the fundamental problem in the management of information exists; uncertainty (Winch, 2010). Out of the feedback can be concluded that especially rating the alternatives was stated to be a process with high uncertainty. If there is a difference between knowledge available and required, the stakeholder cannot fully express its preference. This gap can be mitigated by providing information over time. If the gap remains, the input may be distorted by uncertainty, and subsequently the output. The practical applicability of the model is high when the gap between knowledge present and required is small and vice versa.

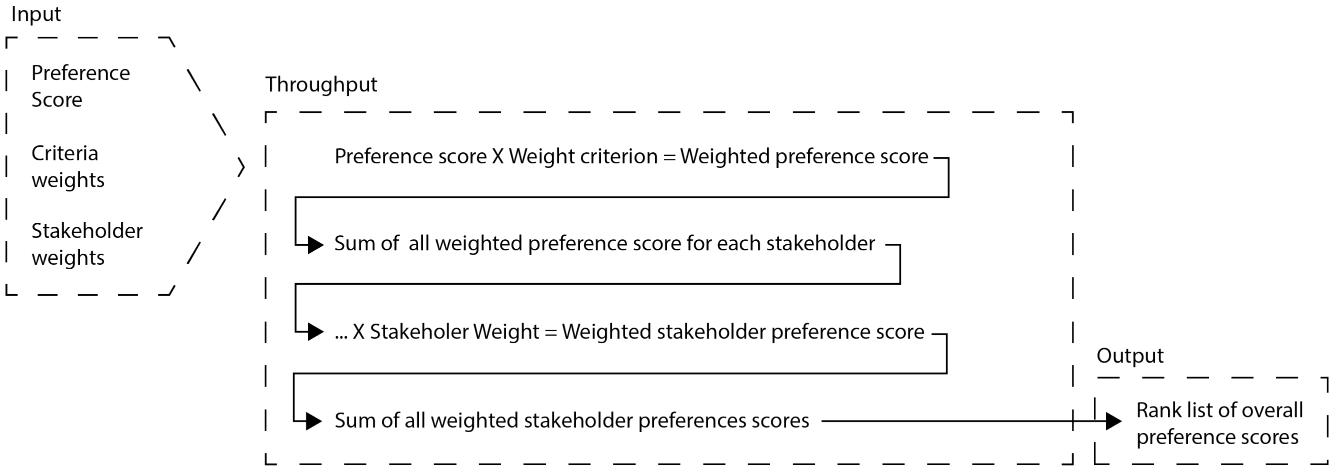


Figure 6.2. Principal structure of the model

Technical: alternatives

The scope of the project is indoor positioning and each alternative has a unique design. The output of the model is a rank list of all alternatives. The recommended alternative is the one with the highest overall preference scores. The outcome of the model supports the last step of the decision-making process: choosing an alternative. However, the most preferred option does not directly needs to be chosen. It is evident that a combination of systems may be possible. If the system allows integration and has the capability to process other sets of data the most preferred alternative may be further improved by including other features of alternatives. The conclusion sheet provides valuable information to discuss improvement.

How can a decision model predict the added value of a smart system?

To give a final answer to the main research question: a decision model can predict the added value of a smart system by defining the preference score of each feasible alternative on each criterion and to calculate the overall preference score for each alternative. The overall preference score represents the value of a smart system and the highest score is predicted to add the most value.

However, the prediction depends on the certainty of the input. High uncertainty will project a distorted prediction of reality. Uncertainty may have a number of factors but in this research a lack of knowledge appeared to be the main factor of uncertainty.

Note that before the added value can be predicted the feasible alternatives need to be selected using the constraints.

6.3 Recommendation

This research comprises of the development of a decision model and a first pilot study. In future research, the model can be tested in other pilot studies, as to validate the conclusions from this research. Next to this, some other recommendations can be made.

PFM vs. PBD

An important question to ask before choosing this research method is: are the alternatives known a priori? If not, than PFM is not an option and this approach cannot be executed. PBD may than be a better option and the PAS approach could provide a sufficient approach. If they alternatives are known beforehand it is good to assess whether the amount of alternatives is complete and fit the intended purpose. If so, the research method can be used to support decision-making in multi-criteria problem.

Standardization of the PFM approach

The second recommendation is to decide how the input is generated. In order to project a case as true as possible all input should be generated specifically for this case. However, the stakeholder knowledge available should be sufficient in order to generate input with certainty. The degree of standardization is a trade-off between knowledge available and required. When little knowledge is available a more standardized model may be recommended. When plenty knowledge is available the PFM research method is recommended.

The second reason to choose a more standardized model is for a quick assessment and reproduction. This is a trade-off between customization and effort. The standardized model requires less input and has a shorter procedure, but is less customized. These type of approaches are more of interest when the decision maker is still in the initiative phase and easily want to reach a preliminary recommendation.

For example, a Real Estate Manager (REM) wants to know which smart system would add most value to a building in his portfolio. He is aware of the problem that there is no insight in occupancy and an inefficient distribution of square meters per department. Based on this information the real estate manager wants to find a preferred system without investing much time and including the input from stakeholders. The standardized model will quickly produce an answer based only on the REM assigning weights. The REM now has a first indication of which systems would solve the problem that he/she identified. If the REM wants to specify the answer, he/she can always expand his decision-making process with the PFM research method.

Scaling vs. Lagrange curve

In the PFM research method, two techniques were used. With the scaling technique the stakeholder rates each alternative. The scaling technique is appropriate for situations in which the amount of alternatives is limited and the information to be assessed is not going to be changed. If the alternatives or information is likely to change, the scaling technique needs to be redone every time. Then the Lagrange curve is more appropriate. The Lagrange curve has to be established once and each change can be automatically assimilated. Based on the dynamics of the project one of the two techniques is recommended. Scaling is recommended with low dynamics and the Lagrange curve with high dynamics.

The second recommendation relates to the subject of knowledge. Stakeholders stated that it is difficult to rate an alternative when they do not know sufficient about the alternative. Differently, the stakeholder can be asked to not rate the alternatives but only formulate when a criterion would get a score of 100 and when a score of 0. Additionally the stakeholder can be asked to formulate when a criterion gets a score of 50. It is essential that the formulation of the stakeholder is quantitative in order to make the X-axis of the Lagrange curve. The Lagrange curve can be made for each criterion and the researcher can place each alternative on the curve and calculate the preference that corresponds with it. This recommendation between these two techniques depends on the acceptability of the stakeholders.

User tool

The research model is a tool, which is supposed to be handled by the researcher. The model can also be designed to be used by the stakeholders themselves. The model could be send to the stakeholder and filled in and adapted at any time. No interviews are necessary to define the input. In order to do so, it is recommended to change the model. The model should get a user-friendly interface in which all tabs and steps are clearly explained. All relevant information must be found within the model as well. The user tool should get a more app-like structure.

Smart building tool

Based on the results of this research an expert tool is recommended for choosing a smart system. The reason for this is to eliminate the lack of knowledge. The amount of knowledge available would probably not be any different at another company. Moreover, at SRE the knowledge available is probably above average due to the inclusion of smart in the entire vision of the company. Even in a company with more than average knowledge, knowledge was still lacking. Therefore, the subject smart buildings is recommended to be approached by an expert and only include the stakeholders if certain.

Testing the model on a successful decisions made

A means to test the reliability of the decision model is to compare it with a decision already being made. The output of the model can be compared with the results of a decision that lies in the past. If the comparison is similar the decision model seems to project the true situation. Note that it is assumed that the decision made is the correct decision.

Improving the recommended option

The eight step (combine) indicates possibilities to improve the most preferred alternative. These possible improvements are not yet tested. For future research it is recommended to test if the combination of alternatives results in a further improved alternative. If so, it is also important to check its feasibility. The combined alternative must comply to the constraints but should also be possible to design. It may be that the new alternative consists of a combination of features that are not available on the market and/or not able to make.

For SRE it is recommended to revise the most preferred option and enter a dialogue with Cisco to see which of the features pointed out could be included in the system and improve the overall preference score of Cisco. Especially the infrared sensor and communication technology are recommended to be discussed.

Chapter VII Reflection

7. Reflection

In the reflection the student uses a short substantiated explanation to account for the preliminary results of the research and design in the graduation phase (product, process, planning). The choice of method (how) and argumentation (why) which preceded the research, was a part of your study plan – the reflection must contain an answer to the question of how and why the approach did or did not work.

The results of the research are twofold. The results elaborate on the process, which is of importance for the field of science, in particular Preference Function Modelling. The results regarding the product is the outcome of the decision model which is of importance for the Case of Schiphol Real Estate. The approach did work and gave an valuable answer. However the planning was a point of discussion. The approach worked within the given time but looking back on the project a more extended approach on providing information about the alternatives could have enhanced the process and outcome.

The reason I have chosen this method is also twofold. Learning about smart systems made me realise that this is a complex alignment problem in which multiple stakeholders with multiple criteria are involved. Choosing a operational research method including a decision model is common to approach these kind of problems. Secondly, my personal preference was to learn more about operational research. To do so, the research question is formulated as a question related to operational research. An operational research question is often a 'how can' question and implies is future oriented and focusses on creating an artefact such as a decision model (Binnekamp, 2012).

Operational research consists of many different approaches. In order to find the right approach I tried multiple versions. During an operational research course I've learned about optimization analysis and preference measurement. After testing both approaches I learned why optimization analysis didn't work and preference measurement did. The main reason was that optimization analysis works with constraints and a single objective while the problem in my research could best be approached by finding the best (most preferred) option regarding multiple objectives, which is possible with preference measurement.

The same testing approach is used with PFM and PBD. During my research I switched between the two methods. This was done in discussion with Arkesteijn. My mentor had experience in both approaches which was very helpful in finding my most suitable approach. At one point I hanged on too long to a certain approach (Lagrange) and because of valuable feedback the approach was made secondary and a more suitable approach came in place. It was a trial and error process in which I finally concluded that PFM was most suitable because of the limited amount of options. The PAS approach of Arkesteijn et al. (2017) would be used as reference for developing a new approach. The process of going through different approaches gave me an answers to why and how my approach should work best.

Now at the end of the research based on the feedback of the stakeholders the same discussion arises. Maybe the Lagrange curve would be more helpful than expected based on the fact that rating the alternatives was perceived difficult? This iterative process I went through is very interesting and related very well to the faculty of Architecture. It is in essence the same as the design process in which you test, evaluate, refine and optimize a design until a final and satisfactory design is produced (see figure 13.1). The same design process is also recognizable in my research approach.

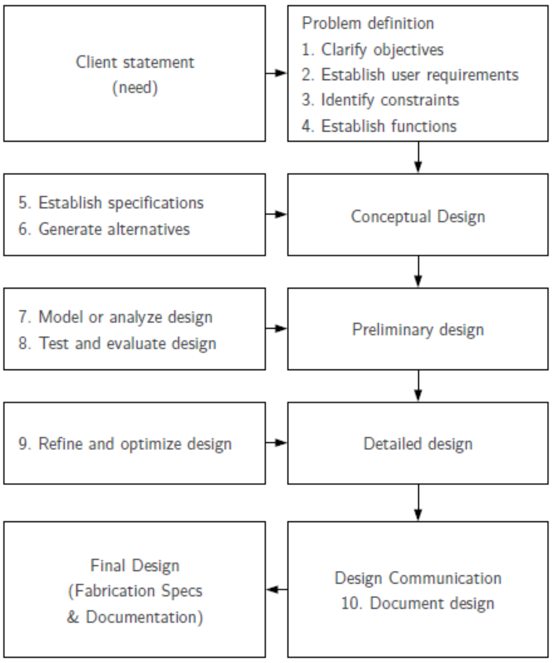


Figure 7.1. Design process (Dym & Little, 2009).

Aspect 1: relationship between research and design

Not applicable.

Aspect 2: the relationship between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS)

The graduation topic is smart buildings and more specific speaking indoor positioning systems. The studio topic is Smart Real Estate Management (SREM). The master track is MBE, which explores the managerial dimension of architecture, construction and built environment.

The graduation topic is chosen based on the studio topic, as I specifically wanted to expand my knowledge about smart systems. The studio is part of Real Estate Management in which an important aspect is the alignment between an organization's real estate to its corporate strategy / user needs (van Bueren et al., 2017). Schiphol Real Estate is continuously solving this alignment problem and sees opportunity to use smart systems to support or solve this. The questions they have are very much in line with the studio topic. Both my graduation project and studio have questions such as:

What smart tools are used in practice and what smart tools are available?

What are the benefits that have been achieved with a smart tool against what?

How can user preferences be integrated into a smart tool?

The graduation topic and master track also have a strong relationship. The graduation topic is part of the decision-making process on a strategic level. It is about deciding which smart system to choose in order to adds the most value for all stakeholders. This type of decision-making is very common on a managerial level in architecture, construction and built environment.

A note I would like to add to the relationship is that the topic smart buildings extends the field of experience of a manager in the built environment. To understand the topic sufficiently, knowledge about the Internet of Things (IoT), sensor technology, cloud computing and interface platforms. This is a very interesting development which I think is getting more common. IT and data is getting more important in many different field of work, including the built environment. In the future an architect, project manager or real estate manager needs to be an IT expert as well (on a certain level).

Aspect 3: Elaboration on research method and approach chosen by the student in relation to the graduation studio methodical line of inquiry, reflecting thereby upon the scientific relevance of the work

My mentors, Monique Arkesteijn and Ruud Binnekamp developed a research method called the PAS approach. The PAS approach is part of Preference Measurement, a methodical line of inquiry common in more technical studies. The approach is relatively new and not tested in large numbers. The research method adopts this approach and a different version of the approach is presented. The research contributes to the testing of the model, provides a general model to support decision-making in a multi-criteria problem. The model and method can be reproduced for other scientific purposes.

The faculty of architecture is a design school and part of a technical university. The way of working is different than alpha studies. The research is part of operational research methods, which is more common at a technical university. Choosing this research method is in line with the learning process and literature at the faculty of Architecture and Delft University of Technology.

Aspect 4: Elaboration on the relationship between the graduation project and the wider social, professional and scientific framework, touching upon the transferability of the project results

The conclusion of my research focusses on the scientific approach of the research method and decision model. However the results from the decision model are applicable to the decision making of Schiphol Real Estate, an important real estate company in the Netherlands. The decision model is usable for decision making processes for similar companies. Even so, the decision model can also be utilised as a source of revenue. The decision model can be used to consult different companies in their decision making process.

The research has a relationship with the scientific framework on two aspects: Preference Function Modelling and alignment models. The projects results contribute to the testing and evaluating of PFM. It also provides a new method to align demand and supply. It does not replace current alignment models but rather extends the existing knowledge.

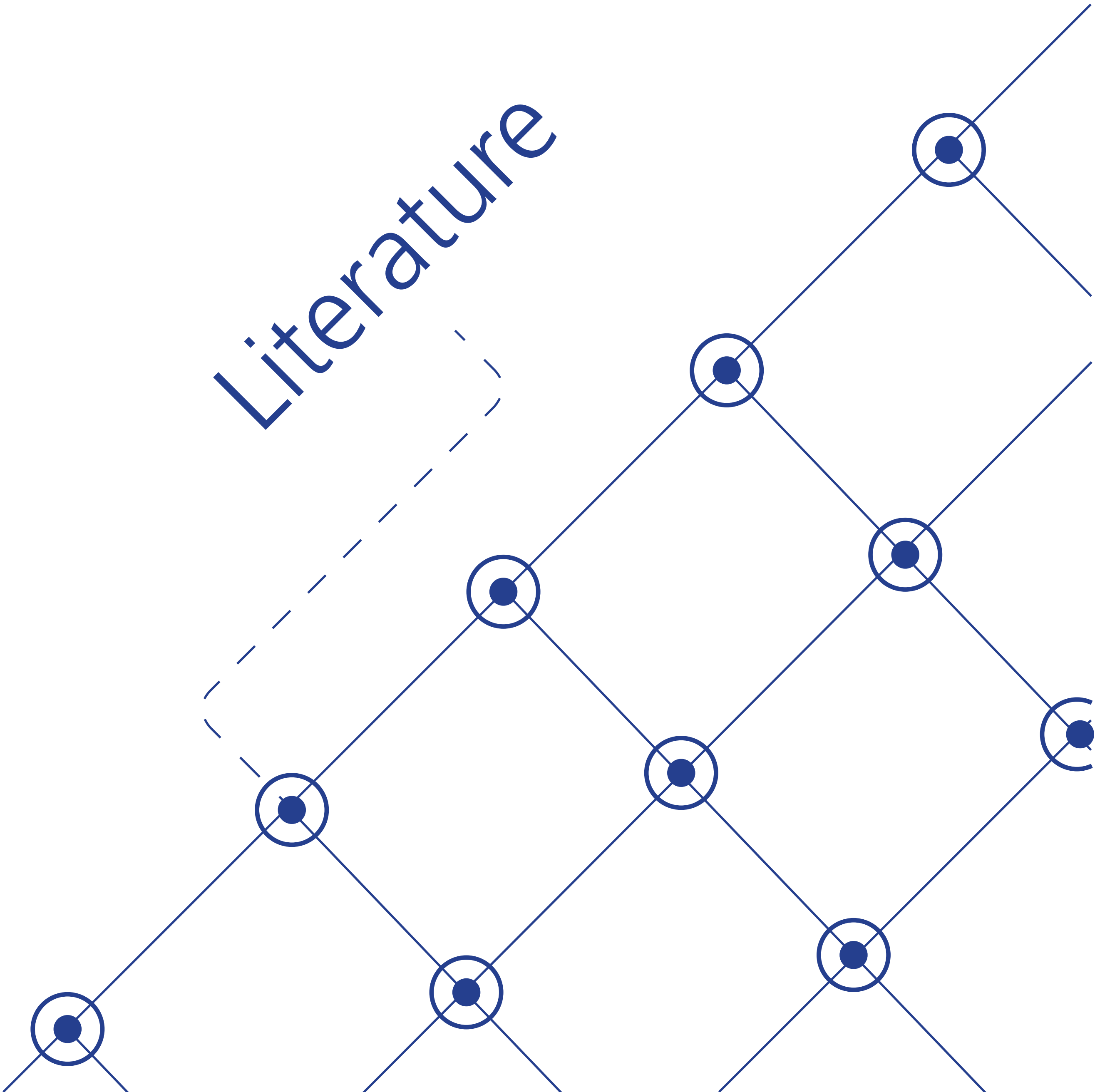
Smart contributes to a number of important social factors such as sustainability and connectivity. The decision model is not designed for the social framework but does include social interests. Smart could improve the sustainability of the built environment and enables better connection between people and their environment. The research provides a new model which could serve as a reference for the upscaling of smart systems in the built environment.

Aspect 5: Discuss the ethical issues and dilemmas you may have encountered in (i) doing the research, (ii, if applicable) elaborating the design and (iii) potential applications of the results in practice

An interesting issue in the field of smart buildings and Internet of Things is the new law: General Data Protection Regulation (GDPR). GDPR aims to bring all the EU member states under one umbrella by enforcing a single data protection law. GDPR is intended to put guidelines and regulations on how data is processed, used, stored or exchanged. During the decision-making process the constraint security and privacy of data is taken into account. However just taking these constraints into account was not enough for Schiphol. Schiphol is cautious about the collection of data and connecting new networks to the existing data centres. After the rank list being presented the security and privacy officer are included in order to assess risks about personal data and possibility to be hacked. Moreover the smart system could serve as a backdoor for hackers if it is not as safe as the rest of Schiphol's data. It is explained as being the weakest link in a chain of data.

Schiphol has a lot of experience in implementing new IT related products. The outlook, the first smart building project, provided lots of valuable lessons learned. One of these is before a smart system may be implemented a hack test needs to be performed. A so called 'ethical hacker' tries to hack the system to discover risks in the system. Before the implementation of a smart system in the SHG the same should be done. Such a test should prevent ethical issues to arise in the future.

Literature



Literature

Abdallah, M., & El-Rayes, K. (2016). Multiobjective Optimization Model for Maximizing Sustainability of Existing Buildings. Journal of Management in Engineering, 32(4), 04016003.

Adams, D., & Tiesdell, S. (2012). Shaping places: urban planning, design and development. Routledge.

Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (2016). Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. Environmental health perspectives, 124(6), 805.

Anderson, D. R., Sweeney, D. J., Williams, T. A., Camm, J. D., & Cochran, J. J. (2015). An introduction to management science: quantitative approaches to decision making. Cengage learning.

Arditi, D., Mangano, G., De Marco, A. (2015) "Assessing the smartness of buildings", Facilities, Vol. 33 Issue: 9/10, pp.553-572

Arkesteijn, M.H., Binnekamp, R. & De Jonge, H. (2017) "Improving decision making in CRE alignment, by using a preference-based accommodation strategy design approach", Journal of Corporate Real Estate, Vol. 19 Issue: 4, pp.239-264

Arkesteijn, M.H., Valks, B., Binnekamp, R., Barendse, P. & De Jonge, H. (2015) "Designing a preference-based accommodation strategy: A pilot study at Delft University of Technology", Journal of Corporate Real Estate, Vol. 17 Issue: 2, pp.98-121.

Arkesteijn, M.H., van der Voordt, T., Remoy, H., Chen, Y.,& Curvelo Magdaniel, F.T.J. (2016) Dear is durable: Liber Amicorum for Hans de Jonge. Delft Technical University, TU Delft press.

Asadi, E., Da Silva, M. G., Antunes, C. H., & Dias, L. (2012). Multi-objective optimization for building retrofit strategies: a model and an application. Energy and Buildings, 44, 81-87.

Barendse, P., Binnekamp, R., De Graaf, R. P., Van Gunsteren, L. A., & Van Loon, P. P. (2012).Operation Research Methods: for managerial multi-actor design and decision analysis. Amsterdam: IOS Press.

Barzilai, J. (2005). Measurement and preference function modelling. International Transactions in Operational Research, 12(2), 173-183.

Barzilai, J. (2010). Preference function modelling: the mathematical foundations of decision theory. In Trends in multiple criteria decision analysis (pp. 57-86). Springer, Boston, MA.

Binnekamp, R. (2010). Preference-based design in architecture. IOS Press.

Binnekamp, R. (2014), Operations Research Methods, for managerial multi-actor design and decision analysis. Delft University of Technology.

Brown, A., & Adams, J. (2000). Measuring the effect of project management on construction outputs: a new approach. International Journal of project management, 18(5), 327-335.

Brueggeman W & Fisher J (1997): Real Estate Finance and Investments. Boston: Irwin McGraw-Hill. 10th ed. Ch 10: Investment and risk analysis, pp 307-355. Economics library 332.72 BRUE

Bryman, A. (2014). Social research methods. Oxford university press.

Buckman, A.H., Mayfield, M., Beck, Stephen B.M. (2014) "What is a Smart Building?", Smart and Sustainable Built Environment, Vol. 3 Issue: 2, pp.92-109

Camporeale, P. E., Moyano, M. D. P. M., & Czajkowski, J. D. (2017). Multi-objective optimisation model: A housing block retrofit in Seville. Energy and Buildings, 153, 476-484.

CPB (2017), De toekomst van kantoren

De Leeuw, A. C. J. (1992). Besturen van veranderingsprocessen - fundamenteel en praktijkgericht management van organisatieveranderingen. Assen: Koninklijke van Gorcum B.V.

Dym, C. L., & Little, P. Engineering Design: A Project-Based Introduction. 2004, Hoboken.

Dym, C. L., Little, P., Orwin, E. J., & Spjut, R. E. (2009). Engineering design: a project-based introduction (third). New York: Wiley.

Engelhard, P. (2018). SRE presentation sheets [presentation]. Schiphol, 14.2.2018

Erasmus (2007). Numerical Methods. Lecture 3 [powerpoint]. Retrieved 15.12.2017 from …

Evans, M., French, N., & O'Roarty, B. (2001). Accountancy and corporate property management-A briefing on current and proposed provisions relating to UK corporate real estate. Journal of Property Investment & Finance, 19(2), 211-223.

Favoino, F., Jin, Q., & Overend, M. (2017). Design and control optimisation of adaptive insulation systems for office buildings. Part 1: Adaptive technologies and simulation framework. Energy, 127, 301-309.

Fisher, R. A. 1935. The Design of Experiments, Edinburgh: Oliver & Boyd.

Gubbi, J., Buyya, R., Marusic, S. & Palaniswami, M. (2012) Internet of things (iot): A vision, architectural elements, and future directions, Future Generation Computer Systems. 29, 1645–1660.

Haynes, B., Nunnington, N., & Eccles, T. (2017). Corporate real estate asset management: Strategy and Implementation. Taylor & Francis.

Jensen, P.A., Sarasoja, A.L., Van der Voordt, T. & Coenen, C. (2013), How can Facilities Management add value to organisations as well as to society? Conference paper. Brisbane, Australia: CIB World Building Congress, 5-9 May 2013.

JLL (2017), Outlook kantorenmarkt 2017

Karatas, A., & El-Rayes, K. (2016). Optimal Trade-Offs between Housing Cost and Environmental Performance. Journal of Architectural Engineering, 22(2), 04015018.

Kejriwal, S., Mahajan, S. (2017) Smart buildings: How IoT technology aims to add value for real estate companies

Kickert, W. J. (1980). Organisation of decision-making: a systems-theoretical approach. North-Holland Publishing Company.

Kim, S., & Kim, S. H. (2017). Lessons learned from the Existing Building Energy Optimization workshop: An initiative for the analysis-driven retrofit decision making. KSCE Journal of Civil Engineering, 21(4), 1059-1068.

Lind, H., & Muyingo, H. (2012). Building maintenance strategies: planning under uncertainty. Property Management, 30(1), 14-28.'

Linder, L., Vionnet, D., Bacher, J. P., & Hennebert, J. (2017). Big Building Data-a Big Data Platform for Smart Buildings. Energy Procedia, 122, 589-594.

Luo, J., Fan, L., & Li, H. (2017). Indoor Positioning Systems Based on Visible Light Communication: State of the Art. IEEE Communications Surveys & Tutorials, 19(4), 2871-2893.

Malidin, A. S., Kayser-Bril, C., Maizi, N., Assoumou, E., Boutin, V., & Mazauric, V. (2008, November). Assessing the impact of smart building techniques: a prospective study for France. In Energy 2030 Conference, 2008. ENERGY 2008. IEEE (pp. 1-7). IEEE.

Meijer (2017). Risk mitigation in location decision-making. Delft University of Technology.

Michael, M., Zhang, L., & Xia, X. (2017). An optimal model for a building retrofit with LEED standard as reference protocol. Energy and Buildings, 139, 22-30.

Montgomery, D. C. (1991). Design and Analysis of Experiments, 3rd. ed., John Wiley and Sons, New York NY

Moreno, V., Ferrer, J., Díaz, J., Bravo, D. and Chang, V. (2017). A Data-Driven Methodology for Heating Optimization in Smart Buildings. In Proceedings of the 2nd International Conference on Internet of Things, Big Data and Security (IoTBDS 2017), 19-29

Nguyen, T. A., & Aiello, M. (2013). Energy intelligent buildings based on user activity: A survey. Energy and buildings, 56, 244-257.

Nouveau. C. (2017). Microsoft Smart Building [powerpoint]. Retrieved 27.11.2017 from https://www.sh-ib.nl/

Razmak, J., & Aouni, B. (2015). Decision Support System and Multi-Criteria Decision Aid: A State of the Art and Perspectives. Journal of Multi-Criteria Decision Analysis, 22(1-2), 101-117.

Schiphol Employee Committee (2017). Werkplekken onderzoek ondernemingsraad [presentation]. Schipol, 25.4.2017

Schmeck, H. & Xu, H. (2017). State-of-the-art user interfaces for building operating systems. In Smart Grid and Smart Cities (ICSGSC), 2017 IEEE International Conference on (pp. 283-292). IEEE.

Schön, D.A. (1987), The Reflective Practitioner: How Professionals Think in Action, Jossey-Bass, San Francisco.

Shaikh, P. H., Nor, N. B. M., Nallagownden, P., & Elamvazuthi, I. (2014). Stochastic optimized intelligent controller for smart energy efficient buildings. Sustainable Cities and Society, 13, 41-45.

Shun, C.K.L. (2016), Property Decision Tree Analysis. Session 10 of ABPL 90036 Property Investment UNIVERSITY OF MELBOURNE, [powerpoint]. Received 3.10.2016 from https://lms.unimelb.edu.au/

Smith (n.d.) BMS [presentation]. University of Melbourne.

Smith, S. (2002), "Intelligent buildings", Design and Construction: Building, in Value, R.B. and Valence, G.D. (Eds), Butterworth Heinemann, Oxford, pp. 36-58.

Suram, S., MacCarty, N. A., & Bryden, K. M. (2018). Engineering design analysis utilizing a cloud platform. Advances in Engineering Software, 115, 374-385.

Valks, B., Arkesteijn, M., Den Heijer, A. & Van de Putte, H. (2016) Smart campus tools: a study on measuring real use of campus facilities. Delft University of Technology.

Valks, B., Arkesteijn, M.H., Den Heijer. A. & Vande Putte, H. (2016) Smart campus tools: a study on measuring real use of campus facilities

Van Bueren, E., Koutamanis, A. and Mauri, Andrea. (2017), MBE graduation subjects.

van der Ven, W. (2017). Smart Airport City [powerpoint]. Retrieved 27.11.2017 from https://www.sh-ib.nl/

van der Voordt, D. J. M., & Wegen, H. B. (2005). Architecture in use: an introduction to the programming, design and evaluation of buildings. Routledge.

van der Voordt, T., Jensen, P. A., Hoendervanger, J. G., & Bergsma, F. (2016). Value Adding Management of buildings and facility services in four steps. Journal of Corporate Real Estate, 6(1), 42-56.

Wang, L., Wang, Z., & Yang, R. (2012). Intelligent multiagent control system for energy and comfort management in smart and sustainable buildings. IEEE transactions on smart grid, 3(2), 605-617.

Winch, G. M. (2010). Managing construction projects. John Wiley & Sons

Yang, R. (2013). Development of integrated building control systems for energy and comfort management in intelligent buildings. The University of Toledo.

Zhao, Q. (2017). Research opportunities arising from control and optimization of smart buildings. Control Theory and Technology, 15(1), 78-80.'

Appendix