A Model-Based Assessment for the Solution Space of a Cognitive Coffee Robot Waiter

Thierry Sop Njindam, Torsten Metzler,
Udo Lindemann and Kristin Paetzold

Abstract Cognitive products are tangible and durable things with cognitive capabilities that meet and exceed user expectations by using cognitive functions, e.g. to perceive, to learn, to reason, etc., to reduce the need for human input. This paper presents a model-based assessment of the solution space for cognitive products. So far, the design of cognitive products has been based on prototype-oriented approaches, which mainly focus on cognitive algorithms, relying too much on designer´s experience, beliefs or ad hoc arbitrated processes and following as a consequence the "design it now and fix it later!"–philosophy. A model-based assessment of the solution space would enable a better and early estimation of design alternatives that meet not only software requirements but also hardware requirements from the very early stages down to system structural and behavioural aspects in highly dynamic and uncertain environments. The conventional MBSE approach has been adapted to cognitive products and is demonstrated using a cognitive coffee robot waiter.

1. Introduction

Cognitive products are tangible and durable things with cognitive capabilities such as perceiving the environment, learning and reasoning from knowledge models that are created through tight integration between a physical carrier system with embodied mechanics, electronics, microprocessors and advanced software algorithms [8]. A typical cognitive product basically perceives its environment as well as the actions performed by the user with whom it interacts through its embedded sensors, then stores acquired information in its knowledge base, reorganizes and enlarges its prior knowledge and skills through learning and then plans its actions either on the basis of processes and sequences of operations stored in its knowledge base or from logical reasoning mechanisms.

The design of cognitive products requires a collaborative effort between engineering sciences, information processing, cognitive and life sciences and artificial intelligence. A holistic view of how the entire system fits together is required with regards to the number and diversity of interconnected elements, the tight integration between hardware and software elements, the close interaction with the surrounding environment and the cognitive behavior over time. To date, there is no holistic approach to support the development process of cognitive products. From the engineering design point of view, systematic approaches (VDI 2221; VDI 2206; Axiomatic Design; Gero´s FBS-Model), even though they provide fundamental aspects of the design as a problem solving activity from the conceptual design and embodiment design to detail design, have several shortcomings since they do not adequately consider the system as a whole as well as the various involved disciplines (information processing, cognitive sciences, etc.) and refer to disconnected simulation models in different design stages.

With regards to the development of cognitive products, traditional long-lasting prototype-oriented approaches with disintegrated hardware and software processes are highly iterative, inefficient, time consuming, error-prone and do not fully comprehend the system under consideration, especially during the early design phases.

The goal of this contribution is to improve the design process of cognitive products and provide a generic model-based approach by addressing the following problems:

- Incoherent and non-holistic representation of the system with its cognitive functions, especially during the early design phases.
- Insufficient traceability between core aspects of cognitive products such as the flexibility of their requirements, functions including cognitive functions, structure, behavior, performance and operational scenarios processed during their lifetime.
- Arbitrary, experience-based or a priori selection of design parameters without analysis and evaluation of system requirements, design options, uncertainties during the product lifecycle, etc.
- Limited re-use of specifications, system models, and design artifacts to support the development of complex embedded systems such as cognitive products.

The analysis and visualization of the solution space in the design process of cognitive products will support decisions to be made in the selection of system design parameters. A cognitive coffee robot waiter is used as an illustrative example.

Section 2 introduces cognitive products and how they are modeled from a functional perspective. Section 3 describes a model-based systems engineering approach to assess the solution space of systems in general. This approach is then applied to partially assess the solution space of the coffee robot waiter in Section 4. Section 5 discusses the results and section 6 concludes this contribution.

2. Cognitive Products

Cognitive products are tangible consist of a physical carrier system with embodied mechanics, electronics, microprocessors and software. The surplus value is created through cognitive functions enabled by flexible control loops and cognitive algorithms, e. g. stemming from AI. Cognitive functions, like *to perceive*, *to learn*, *to reason*, etc., allow cognitive products to act in an increasingly intelligent and human-like manner. They can adapt to dynamic environments as well as to the changing product state and can be integrated in human living environments easily. They interact and cooperate with humans, have a better performance than non-cognitive products and are able to maintain multiple goals and make appropriate decisions and thus exceed current user expectations [8, 11].

To support the interdisciplinary development of cognitive products a taxonomy of cognitive functions and flows is presented in [9]. The taxonomy enables and fosters a model-based development of formal functional models in the conceptual design phase of cognitive products. Functional architectures, combining a functional model with a structural model, make the reuse of the allocation from function to structure possible as well as the identification of patterns. Another method, addressing how cognitive functions can be identified in activity diagrams and integrated in cognitive product concepts, has been published in [10].

3. Model-Based Assessment of Solution Space in the early Design Phase

This section describes a general model-based systems engineering (MBSE) assessment of the solution space using systems engineering and extends it for cognitive products by including the flexibility needed to handle the cognitive behaviour. Generally, the earlier a new technology is adopted in complex systems development, the more likely it is to create an inconsistent and error-prone design, at least before adequate design methodologies are developed. Model-based systems engineering has been widely recognized as an effective means to manage the complexity of systems by using descriptive and simulation models to support the specification, design, analysis and verification of systems consisting of both hardware and software components [4]. The conventional framework as depicted in fig. 1 has been adapted to emphasize cognitive functions as well as environmental conditions among the core characteristics of cognitive products. This top-down approach maintains consistency between the system views and activities within the design process such as requirements specification, functional analysis, functional-structural allocation, architecture definition, evaluation and optimization of design alternatives, verification and validation. New challenges faced in designing cognitive products emerge on the one side from the flexibility of requirements and related operational scenarios in a cognitive context and on the other side from unpredictable and dynamic environmental conditions

The adapted MBSE-Workflow begins with the well-known typical early design tasks which focus on the identification of user needs as a basis for the technical requirements specification. This stage defines and at the same time consequently constrains the design space [6].

Next, the identified user needs and system requirements are turned into functions. Functions are a solution-neutral description of what the system does and can be represented conveniently in blocks with interfaces between them. The emphasis in generating functional architectures of cognitive products is placed on the identification of flows of information and energy among cognitive functions and between cognitive functions and other non-cognitive functions. A deep understanding of the interactions between the system and its surrounding dynamic environment, by means of inputs and outputs, is crucial to determine the system boundary [12]. It is usually necessary for complex systems, to decompose their primary functions into sub-functions. This increases the level of detail of the model and provides a good overview about the flows (information, energy or matter) on which the functions operate [3]. As a result, this functional model, on the one side, provides a link between the system´s specifications and the subsequent physical embodiment. The resulting functional model is an abstract and static view of "what the system should do" and illustrates the internal relations between the functions.

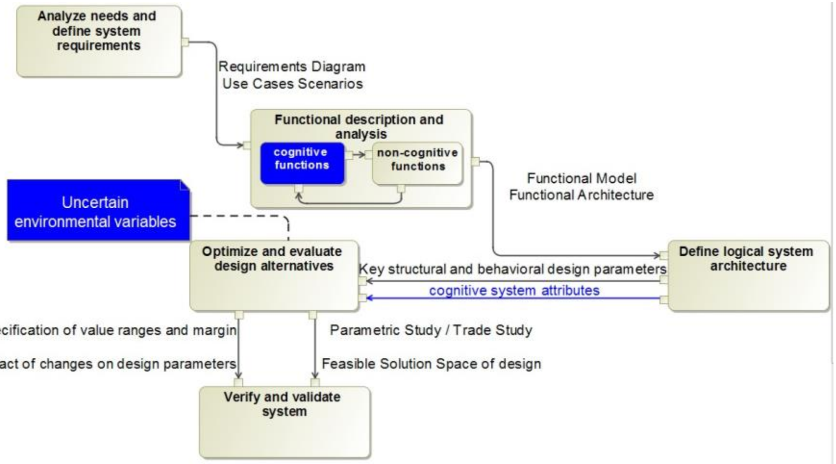

Fig. 1 Activities within the MBSE Process, according to [1] and [12]

On the other side, functional models strategically guide further allocation of system functions to physical components even though there exists no direct or objective mapping from functional elements to physical elements [5], [15]. This implies that more than one design may ensue from the mapping between the functional domain and the physical domain. Defining the system architecture, which further reduces the solution space of design, includes the specification of structural design parameters such as geometric attributes of parts and physical relationships between the parts. However, the cognitive system behaviour is implemented to a great extent in the system software elements. Even though related cognitive system attributes can not be estimated at these design stages, it is crucial to set critical system parameters, limit values and boundary conditions within which the cognitive system behaviour is assumed to be performed. The context-dependent solution space of the design is then tremendously influenced by these cognitive system variables and is the result of the optimization of possible design alternatives in a well-defined context with a wide range of possible scenarios. It is assessed by trading off structural and performance design parameters, based on equations of the system dynamics and technical constraints with regard to previously defined performance requirements, and by coupling them with environmental variables and cognitive system attributes. A relatively high level of imprecision of the environmental and system design parameters is assumed in the early design phase. Several methods such as fuzzy arithmetic, interval mathematics or probability-box have been introduced to cope with such uncertainties and imprecision issues to estimate value ranges and margin of design parameters [2],[13]. The final verification and validation activities are intended to make sure that the selected design alternatives satisfy the previously defined system requirements in the specified context.

4. Assessing the Solution Space of a Cognitive Product using an Application Example

In this section is shown how the assessment of the solution space in cognitive product development is accomplished using a coffee robot waiter as an example. The coffee robot waiter (see fig.2 left) is a cognitive product serving coffee autonomously in a known environment [9]. It was developed by students and assistants with the goal to implement and test cognitive functions in a physical product. The robot is able to serve coffee based on orders placed on a website. This is possible because the robot knows its working environment that it learned prior to the use-case when serving coffee. If more than one order is placed at the same time it calculates the optimal route according to an online traveling salesman algorithm which depicts some aspects of the cognitive system behavior by planning the delivery route and then moves to the target positions (compare tours in fig. 2 right). In addition, it checks if enough coffee and energy is available to satisfy user requests. On its way it avoids static and dynamic obstacles. It remembers reoccurring obstacles at certain locations and adds them to the map to consider them in the next path calculation. Based on the robot´s experience, it estimates the time till coffee is delivered for every target and sends a message to the user screen.

The focus of this paper regarding the assessment of the solution space of the coffee robot waiter is on the top-level functional requirement "cognition" with its derived sub-requirements "autonomy", as illustrated in fig. 3. Other sub-requirements are not relevant for this work. The objective herein is limited to the specifications of "WHAT" the system should do in terms of its cognitive functions. Given this problem and assumed requirements specifications, we identify the following core cognitive functions:

- Perceive working environment
- Learn working environment
- Decide best route
- Think about orders
- Act in environment

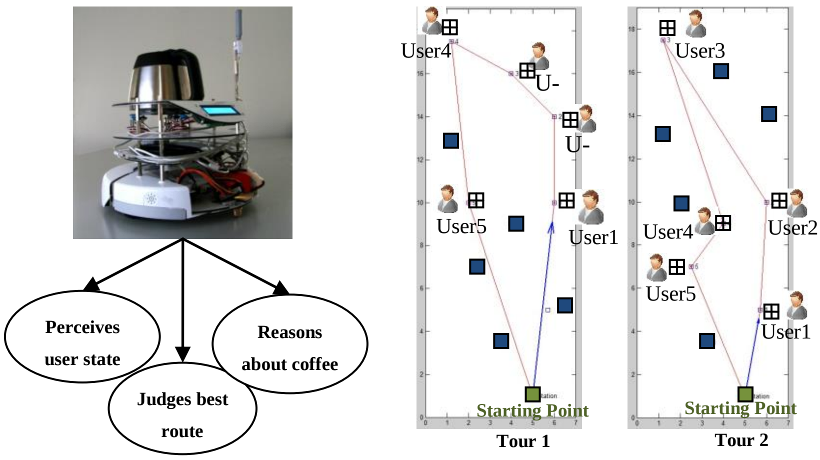

Fig. 2 Overview of the cognitive coffee robot waiter

Next, a functional architecture, as an essential element of the conceptual design of the system is developed and serves as basis for the derivation of the system architecture. In the application example the Systems Modeling Language (SysML) in combination with the taxonomy of cognitive functions and flows is used. Cole Jr. underlines in [3] the importance of this integrated functional view in the design process even though things are fuzzy at this stage of the design process. Hierarchical functional identification diagrams and functional flow diagram are typical diagrams belonging to a front-end functional analysis.

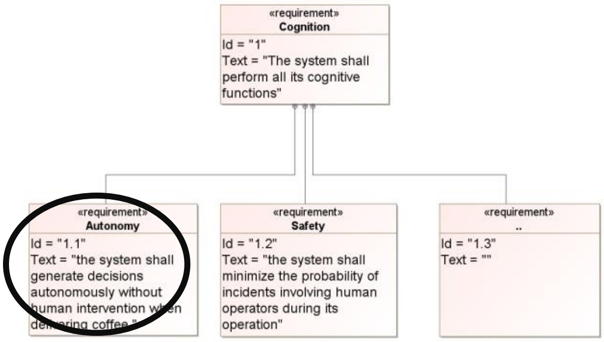

Fig. 3 Top-level requirements of the cognitive coffee robot waiter

4.1 Defining the system cognitive functions with the functional identification diagram

Functional analysis, as viewed in the MBSE process (fig. 1), includes a top-down view, from the highest to the lowest abstraction level which is usually required to hierarchically decompose high level functions into sub-functions and illustrated by functional identification diagrams. Fig. 4 illustrates the function hierarchy of the coffee robot waiter.

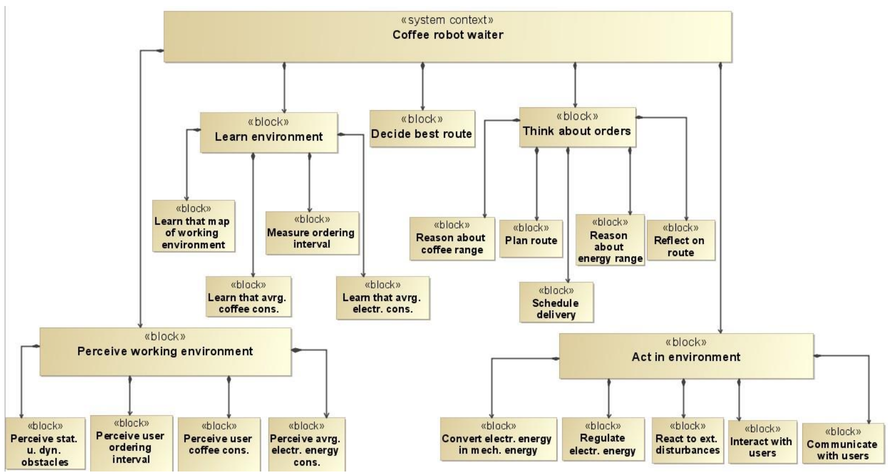

Fig. 4 Functional identification diagram of the coffee robot waiter

4.2 Representing the system functional model with functional flow diagram

As functions are more detailed, functional flow diagrams show the linkage between these functions and also provide valuable information on the arrangement of functional elements, their sequence of actions and the interaction amongst the system functions. The lines connecting the functions illustrate the functional flows by means of information, data and energy flows. Figure 5 illustrates the functional flows of the coffee robot waiter.

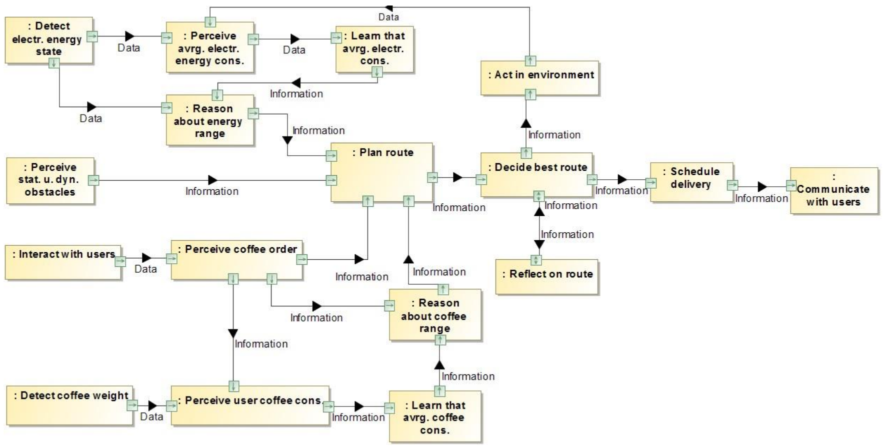

Fig.5: Functional Flow Diagram of the coffee robot waiter

4.3 Allocating functional to structural parts

Allocating functional elements to structural elements is a common aspect in the design process called system architecture which provides an overview about the concrete relation between cognitive functions and the structural elements they need to be realized in the physical world. The complexity of cognitive products is reflected in this stage with the number and diversity of interrelated system elements. Linking cognitive functions with physical elements is basically essential to identify the necessary hardware modules and generate the system physical architecture. An example of the functional-structural allocation for the cognitive function “Act in environment” is illustrated in fig. 6. The complete functional-structural allocation of the system is illustrated in a functional-structural allocation matrix in fig. 7.

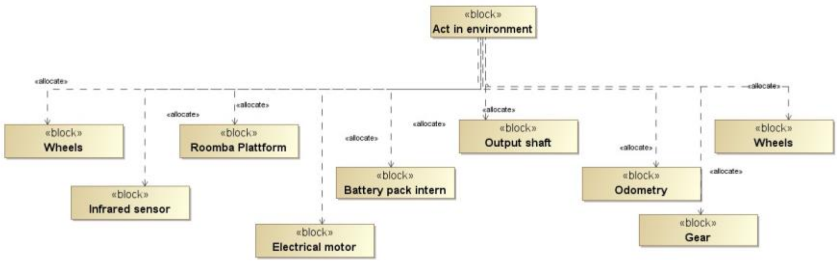

Fig. 6 functional-structural allocation of "Act in the environment"

The complete hardware configuration of the coffee robot waiter with characteristic design parameters is shown in fig. 8. The associated design parameters related to the hardware components are displayed as values and serve as basis for the subsequent value-oriented exploration of the solution space of design. The linkage between the models of the coffee robot waiter and external numerical solver for the computation of the solution space of design is done with the SysML-Parametrics diagrams.

	Additional wheel …	Additional wires […	Battery controlle…	Battery pack ext…	Battery pack inte…	Coffee pot [Star…	Current sensor […	D-Link USB-Stick …	Electrical motor […	Gear [Starbugs::…	Glass plate [Star…	Infrared sensor […	Internal watch [S…	Laptop-computer…	Laser range scan…	LCD text display …	Micro-PC [Starbu…	Odometry [Starb…	Output shaft [St…	Roomba Plattfor…	User computer [S…	Weight sensors […	Wheels [Starbug…
Functions	2	3	2	3	5	1	3	10	3	2	4	1	7	26	4	3	12	5	1	3	3	5	1
Act in environment	↗				↗				↗	↗		↗						↗	↗	↗			↗
Communicate with users								↗					↗	↗		↗	↗				↗		
Convert electr. energy in m…					↗				↗														
Decide best route														↗									
Detect coffee weight		↗				↗					↗			↗			↗					↗	
Detect electr. energy state		↗		↗	↗		↗	↗						↗			↗						
Detect obstacle distance								↗						↗	↗		↗						
Interact with users								↗						↗		↗	↗				↗		
Learn environment																							
Learn that avrg. coffee cons.														↗								↗	
Learn that avrg. electr. cons.														↗									
Learn that map of working …														↗									
Learn user ordering interval														↗									
Measure ordering interval													↗	↗									
Perceive avrg. coffee cons.														↗									
Perceive avrg. electr. ener…														↗									
Perceive coffee order														↗									
Perceive electr. energy state														↗									
Perceive stat. u. dyn. obst…								↗						↗	↗		↗	↗					
Perceive user coffee cons.		↗						↗			↗		↗	↗			↗	↗				↗	
Perceive user ordering inter…													↗	↗									
Perceive working environment								↗						↗	↗		↗	↗		↗			
Plan route														↗									
React to ext. disturbances	↗				↗			↗	↗	↗				↗	↗	↗	↗	↗		↗			
Reason about coffee range								↗			↗		↗	↗			↗					↗	
Reason about energy range			↗	↗			↗	↗			↗		↗	↗			↗					↗	
Reflect on route														↗									
Regulate electr. energy			↗	↗	↗		↗										↗						
Schedule delivery													↗	↗									
Think about orders														↗							↗		

Fig.7: Functional-Structural Allocation Matrix of the coffee robot waiter

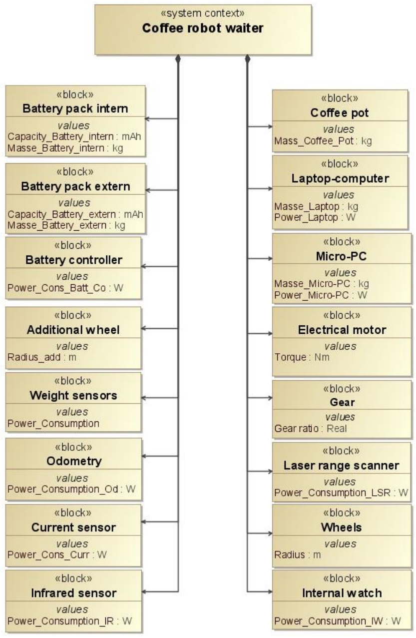

Fig. 8: Hardware modules composition of the coffee robot waiter

4.4 Use of causal loops to optimize design alternatives

The main task to assess the solution space of structural elements of the coffee robot waiter is to trade-off performance and structural design parameters with a view to requirements specification and technical constraints. At the same time, designers must make sure the coffee robot waiter has enough energy left to perform its cognitive functions while delivering coffee orders as fast as possible. As already stated in the description of the cognitive coffee waiter, a map of the environment with environmental variables such as the estimated position of the users is incorporated into its knowledge module. The coffee robot waiter is equipped with a coffee pot having a capacity of five cups and being able to deliver coffee at maximum to five users out of ten potential users in one tour after which it automatically returns to its starting point to refill the coffee pot and recharge its batteries. Fig. 2 illustrates the map of the environment with two tours we reproduced in an external numerical computing environment. Possible scenarios with boundary conditions are hereby defined with these assumptions.

Variable Parameters	
Voltage	[24:3:96] V
Electrical motor rotational speed	[2000:750:10000] 1/min
Power consumption of electronic components	[24:0.4:64] W
Gear Ratio	6:1:16
Speed range	0.1:0.05:0.4 m/s
Mass of the hardware components	[5.243:0.036:7.171] kg

Fixed Parameters	
Acceleration of gravity	9.81 m/s²
Desired Acceleration during the delivery	0.2 m/s²
Coefficient of friction	0.01
Wheel radius	0.035 m
Transmission efficiency	0.8
Mass of the coffee pot	0.728 kg
Mass of one coffee cup	0.3 kg

Table 1: Parameters employed for the optimization

From this, the coffee robot waiter chooses up to five users (represented in fig. 2) from the ten assumed available users (boxes on the map; blue boxes represent the locations of the unselected users during the delivery tour) and drives back to the starting point (colored in green, fig. 2). The traveling salesman algorithm has been computed to calculate the optimal route (see fig. 2) for the delivery. We did not include static and dynamic obstacles for this work. The simulation of the environment with the assumed user locations was numerically solved with the well-known Traveling Salesman Problem and has the objective to estimate the distance covered by the cognitive coffee robot waiter during the coffee delivery which is the basis for the energy consumption while moving. However, one of the most difficult problems encountered at this design stage when optimizing complex systems is, as explained above, the suitable estimation of their component design parameters whose values cannot be predicted with certainty. To cope with this issue, interval analysis has proven useful in bounding the values, by means of their minimum and maximum, of uncertain design parameters [2]. The system design parameters employed for this case study can be selected either on the basis of the designer´s experience or on empirical values and are to be varied as shown in Table 1. Common parameters such as coefficients of friction, mass of the coffee pot can be assumed as fixed.

Based on these assumptions, a trade-off between the design parameters is done, the constraints related to the system´s dynamic behavior and the optimization objectives. Fig. 9 shows the results of the performed simulation of the solution space. For a better understanding of the use case scenario, the distance travelled by the cognitive coffee waiter was divided in five different sub-distances, corresponding to the delivery of one coffee cup to a user. It is assumed that no obstacle disturbs during the delivery. It is also assumed, due to the significant energy consumption of activities requiring high level computation such as cognitive processing, that the energy consumption of the motion of the robot accounts only for half of the total energy consumption [7]. The feasible solution space of design shows that the results of the trade-off analysis are not obtained from the maximization or minimization of the assumed design parameters. We used a variance coefficient (var = 0.2) to express the deviation from these extreme values (maximum and minimum). This reflects the fact that the global optimum does not fulfill the previously defined requirements. Based on these results, designers are able to support their decision making process concerning the mass of the structural components and the energy consumption, by means of the battery capacity the cognitive coffee waiter needs to perform its cognitive tasks, thus satisfying the optimization objectives.

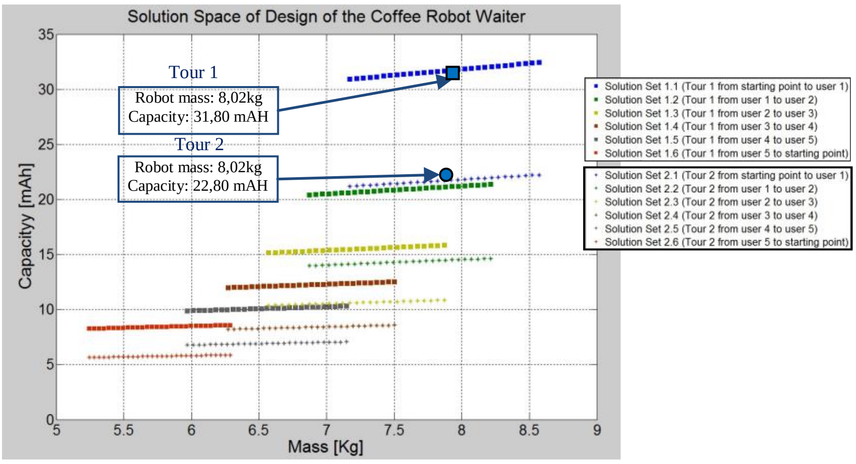

Fig. 9 Context-dependent feasible Solution Space of design of the coffee robot waiter

5. Discussion

The context-dependent assessment of the solution space of the coffee robot waiter, while considering two delivering tours (fig. 2 left), is illustrated in figure 9. The required capacity of the battery throughout the delivering from one user to the next and back to the starting point is illustrated. For example, with an assumed robot total mass of 8,02 kg, the battery must have at least 31.8 mAh in the first delivery simulation (tour 1, see fig. 2) from the starting point to user 1 and 22.8 mAh in the second delivery simulation (tour 2, see fig. 2) from the starting point to user 1. As expected, the mass of the robot as well as the distance between the users play a huge role in power consumption. The estimation of the driving distance with the TSP algorithm (see delivery tour 1 and 2 in fig. 2) has proven to be necessary for the approximation of the delivery distance. On a broader scale, simulating as many as possible scenarios and delivery tours is appropriate to consider many use cases before building a physical prototype. The assessment of the solution space is also possible regarding other design parameters from Table. 1. However, designers must be aware of the unpredictable delivering sequence of orders in the sense that users ordering can not be fully predictable. After simulation, it is possible to estimate depending on the mass and the delivering state how much energy the cognitive coffee waiter requires. Further work is needed to reasonably estimate the power consumption of electronic components, especially during high computation tasks such as the cognitive processing. This cannot be achieved without several testing procedures.

6. Conclusion

In this contribution, an approach is proposed to analyze and visualize the solution space of cognitive products using the cognitive coffee waiter as an example. The feed forward approach starts with the requirements specification up to the optimization and evaluation of design alternatives which are represented in the design solution space. On this basis, designers can computationally generate and verify several use cases and analyze the solution space to support their decisions concerning the choice of system design parameters.

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