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PAMMS - Procedure for Automation of Mathematical Modeling and Solution of mechanical system: Application for the design of an innovative fruit and vegetable washer

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ABSTRACT: This paper proposes the Procedure for Automation of Mathematical Modeling and Solution or PAMMS for the design and development of complex mechanical systems. By using PAMMS, experts in different fields within product lifecycle are able to join together into the design process to create the most appropriate system structure or mutually-agreed design solution among experts. In order to prove the applicability of PAMMS, it was employed for the design of an innovative fruit and vegetable washer. At two particular production scenarios, the corresponding models of the washers were designed and manufactured properly. This pointed out that PAMMS is a truly-effective tool for design and development of mechanical system in general.

KEYWORDS: Automation and control; Product lifecycle; Mechanical system; Design and development; Fruit and vegestable washer

INTRODUCTION

Mechanical design or machine design is one of the important branches of engineering design. In the literature, there is a large amount of documents contributing to scientific society in terms of design method classification [1–6]. Besides, among many machine design and development procedures in practice, there are two common ones: traditional and advanced [7–8]. In the so-called “a breaking barrier” traditional procedure, it includes main steps as follows: understand the requirements, analyse and evaluate the design mechanism, design of elements, experimental test with small-scale prototype, evaluate element by criteria, re-design, material analysis and selection, design interaction for manufacturing, creation of detailed mechanical drawings, and finally element manufacturing. While, the advanced procedure comprises of several stages including recognition of need, definition of problem, synthesis, analysis and optimization, evaluation, and the last stage is manufacturing and launching of elements. The characteristic of the former is that every step is independent one to another and each of them is in charge by one certain professional expert, whereas in the latter each stage can turn into an iteration loop that works continuously up to the moment when product quality is achieved in accordance with initial requirements [9].

On the other hand, the concept of product lifecycle management has been widely used in design and manufacturing processes in the recent years [10-13]. Actually, a variety of specialists in different fields such as technical analysis, economic, marketing, commercial art, maintenance, material science and others participate into the product design and development. Accordingly, quality control is conducted from the beginning of the conceptual design and implemented throughout the product design process. In the actual practice, the design process of complex mechanical systems such as vehicles, ships, trains, airplanes must be split into the small modules, in order to parameterize series of parts conveniently by using conventional machine part design methods or based on the professional experience. However, this manner still presents several following drawbacks:

- Lack of interactive exchange of information among experts: During the design process, although the experts play an important role, they can rarely express their opinions to design engineers due to the limitation of time, schedule, and contradiction. In some cases, they are able to evaluate the correctness of mathematical modeling and solution just after the creation and verification of the product. This might cause waste of time and resources, above all the resultant product is not the best as desired.

• Lack of flexibility in mathematical modeling: Once production context alters, product criteria and technical requirement, or in other words components of mathematical model might vary. This results in a mathematical model that may also diverge in its contents, rather than merely the ranges of parameters, requirements or quality criteria. Currently, conventional method only focuses on development of mathematical model for a particular production context.

• Correctness of mathematical modeling: A precise mathematical modeling in fact is a crucial "connection" among experts in different fields within product lifecycle. Actually, mathemathical modeling is an essential task with regard to: *i)* structural components of the system (parts, joints, amount of joints); *ii)* physical phenonmena of the system; *iii)* quality criteria that may change continuously in different production contexts; *iv)* the overlaps of technical requirements. If the model is being in charge by only one group of design engineers without the intervention of related experts, the outcome might be inaccurate. Because, while facing technical difficulties in dealing with mathematical modeling, most of the times the engineers intend to simplify physical phenonmena in the model.

From the author experiences on machine design and development, building and solving the mathermatical model are still the most indispensable issues [14-16]. The reason for that is; firstly, a mathematical model is able to describe any mechanical system based on parameters and operational features, secondly, the model can turn into the problem, solution of which would be the optimal design option according to the expert requirements [17]. Therefore, in order to address the aforementioned limitations, in this paper, the authors propose a Procedure for Automation of Mathematical Modeling and Solution or PAMMS. This is a series of approaches to automate three crucial steps in the design of mechanical system such as conceptual design, development and solution of multi-objective mathematical model. PAMMS is also considered as a tool that allows experts within product lifecycle all together take part in building-solving-adjusting the models with the aim to define mutually-agreed design solutions among experts prior to the actual design and manufacture of the product.

METHODOLOGY

In fact, PAMMS involves several auxiliary approaches that developed by using the criteria in modeling language (ML) such as UML (unified modeling language), SysML (Systems Modeling Language) [18-19]. However, the key point that differentiates PAMMS from ML is mathematical model of the mechanical system, which is used for the design and development. PAMMS composes of three main steps that highlighted in Figure 1.

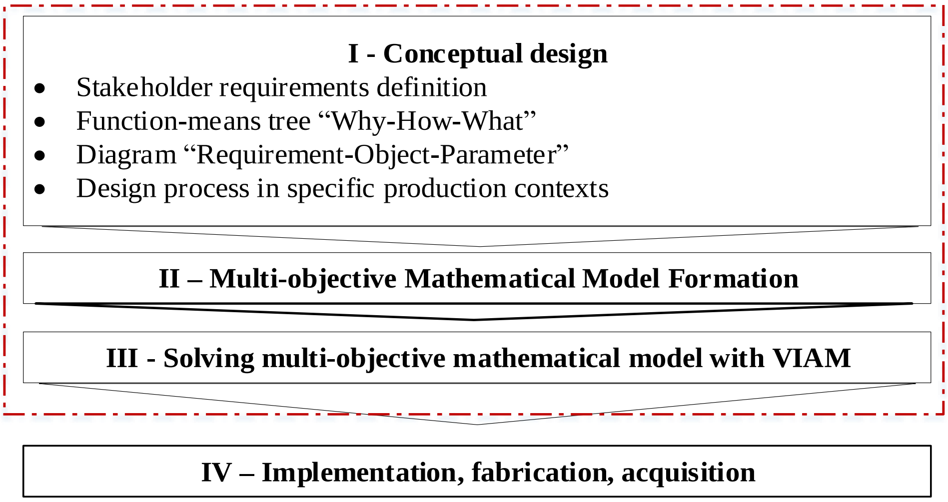


Figure 1. Step-by-step design and manufacture in accordance with PAMMS

(1) Conceptual design

Stakeholder requirements definition: According to Freeman [20] and Ellis [21], stakeholders may be any actors, both human and non-human, that can affect or affected by the new product/service/product-service system. In the design stage of the new product development process, the utmost issue is to incorporate various benefits for stakeholders [22]. However, in order to find out the stakeholders' desires, market survey based on questionaires seems to be the most effective step to start.

Function-mean tree "Why-How-What" (WHW): Function-mean tree is a tree-like or hierarchical language that used broadly in engineering design [23-25]. The tree WHW, as illustrated in Figure 2, is included into PAMMS to summarize preliminary structure of the mechanical sytem, its future operating principles, as well as steps to achieve the goal. Looking into Figure 2, start from WHY, this column reveals the market demand and/or customer's orders (Desires of stakeholders in the previous step), then in the column HOW it shows the principles and suitable solutions for serving the desires, lastly the WHAT/WHAT DO provides part/details and activities that need to be done in order to have the mechanical system as desired.

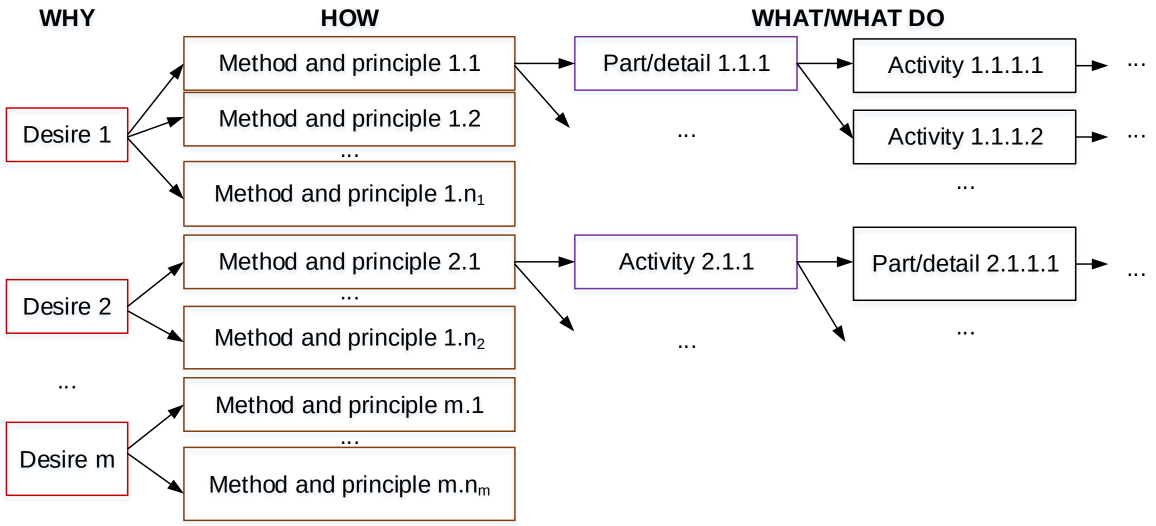


Figure 2. Scheme of function-mean tree WHW

Diagram "Requirement-Object-Parameter": In order to obtain the first prototype of the system that complies with the tree WHW, PAMMS proposes to develop the diagram "Requirements-Objects-Parameters" or ROP [26]. In the diagram ROP, a series of arrows are used to correlate among requirements, objects and parameters. Based on this, the experts analyse the importance of parts and the effect of parameters on the requirements. This would bring out the priority order of desires, allowing the experts to make a decision precisely while dealing with simplification of mathematical model. It is evident that sub-procedures WHW and ROP can be performed easily. However, the abundance of databases still depends upon quantity and level of experts that participate into product design and development process.

Design process in specific production contexts: In theory, the more deliberate sub-procedures ROP and WHW are studied, the better the mechanical system becomes, subsequently forming a huge database for developing mathematical model. Accordingly, the manufacturers are able to build the design procedure. In case, there is a lack of human resources, budget, time, ect. to perform the contents of WHW and ROP, the experts would examine the database thoroughly in order to provide the most appropriate design procedure in accordane with the current circumstance (Figure 3).

By using the abovementioned schemes, the experts can make a decision on the order of **D/C/P** (Desire/Condition/Phenomena). This is a critical issue for the action plan (Activity **A**i) as follows: (i) Determine the concerned parameters $\mathbf{x}_i = \left\{x_{1_i}, x_{2_i}, \ldots, x_{k_i}\right\}$; (ii) Determine the range of parameters $x^{*}_{1_i} \le x_{1_i} \le x^{**}_{1_i}; x^{*}_{2_i} \le x_{2_i} \le x^{**}_{2_i}; \ldots; x^{*}_{k_i} \le x_{k_i} \le x^{**}_{k_i}$ (Based on the conditions **C**i); (iii) Define functional constraints $f_{1_i}\left(\mathbf{x}_i\right), f_{2_i}\left(\mathbf{x}_i\right), \ldots, f_{m_i}\left(\mathbf{x}_i\right)$ for the technical requirements in relation to physical phenonmena **P**i and/or conditions **C**i; (iv) Define objective functions $\Phi_{1_i}\left(\mathbf{x}_i\right), \Phi_{2_i}\left(\mathbf{x}_i\right), \ldots, \Phi_{n_i}\left(\mathbf{x}_i\right)$ for the desired criteria **D**i.

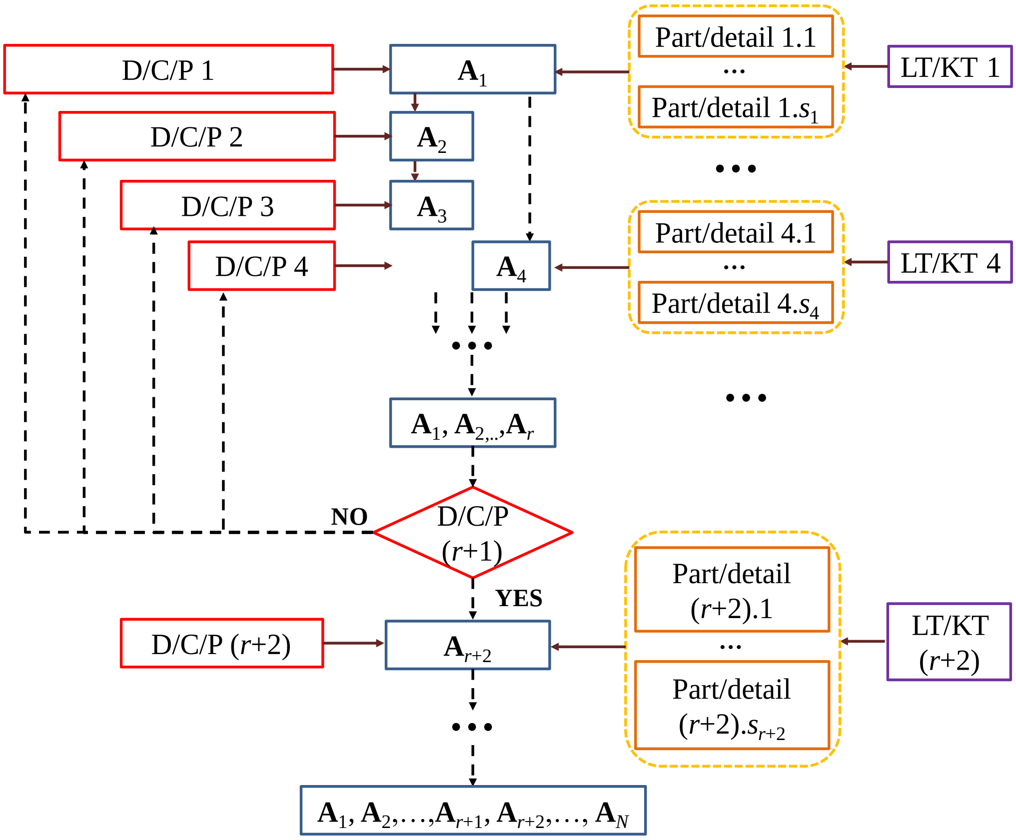


Figure 3. Design procedure in a specific production context (D/C/P - Desire/Condition/Phenomena, A – Activity, LT/KT- Know-How)

Activities **A*i*** are developed in compliance with (**D/C/P**)**i** and/or **(Part/Detail)i** by experts in different fields within product lifecycle. These activities occur sequentially and successively based on the result and verification at the corresponding (**D/C/P**). In case, any activity is not verified, it is necessary to go back to check the previous step. It is noteworthy that determination of parameters, constraints and objective functions is just a mathematical modeling based on a theory of methods including analytical, numerical, regression and design of experiments.

(2) Multi-objective Mathematical Model Formation

In PAMMS, mathematical model is described as follows: Firstly, based on a particular parameter vector $\mathbf{x} = \{\mathbf{x}_1 \cap \mathbf{x}_1 \cap \ldots \cap \mathbf{x}_N\}; \mathbf{x}_i = \{x_{1_i}, x_{2_i}, \ldots, x_{k_i}\}; i = 1..N$ (Initial test point), it is possible to define constraints $\mathbf{f} = \{\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_N\}; \mathbf{f}_i = \{f_{1_i}(\mathbf{x}_i), f_{2_i}(\mathbf{x}_i), \ldots, f_{m_i}(\mathbf{x}_i)\}; i = 1..N$ and objective functions $\boldsymbol{\Phi} = \{\boldsymbol{\Phi}_1, \boldsymbol{\Phi}_2, \ldots, \boldsymbol{\Phi}_N\};$ $\boldsymbol{\Phi}_i = \{\Phi_{1_i}(\mathbf{x}_i), \Phi_{2_i}(\mathbf{x}_i), \ldots, \Phi_{n_i}(\mathbf{x}_i)\}; i = 1..N$; then it needs to recheck the condition of **f** and successive vector **x** in order to optimize **Φ**. Multi-objective mathematical modeling developed by experts can be obsersed in Figure 4.

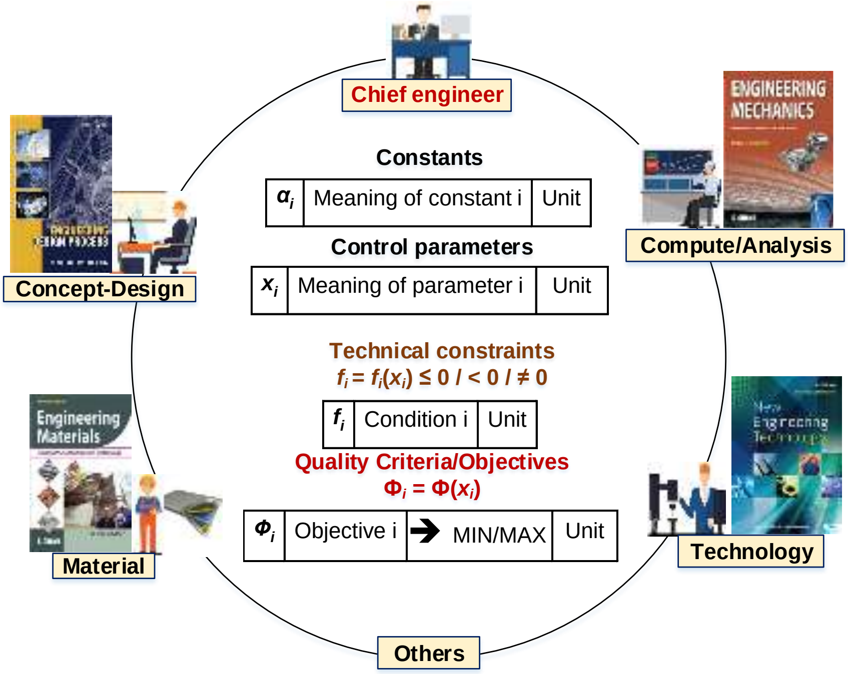
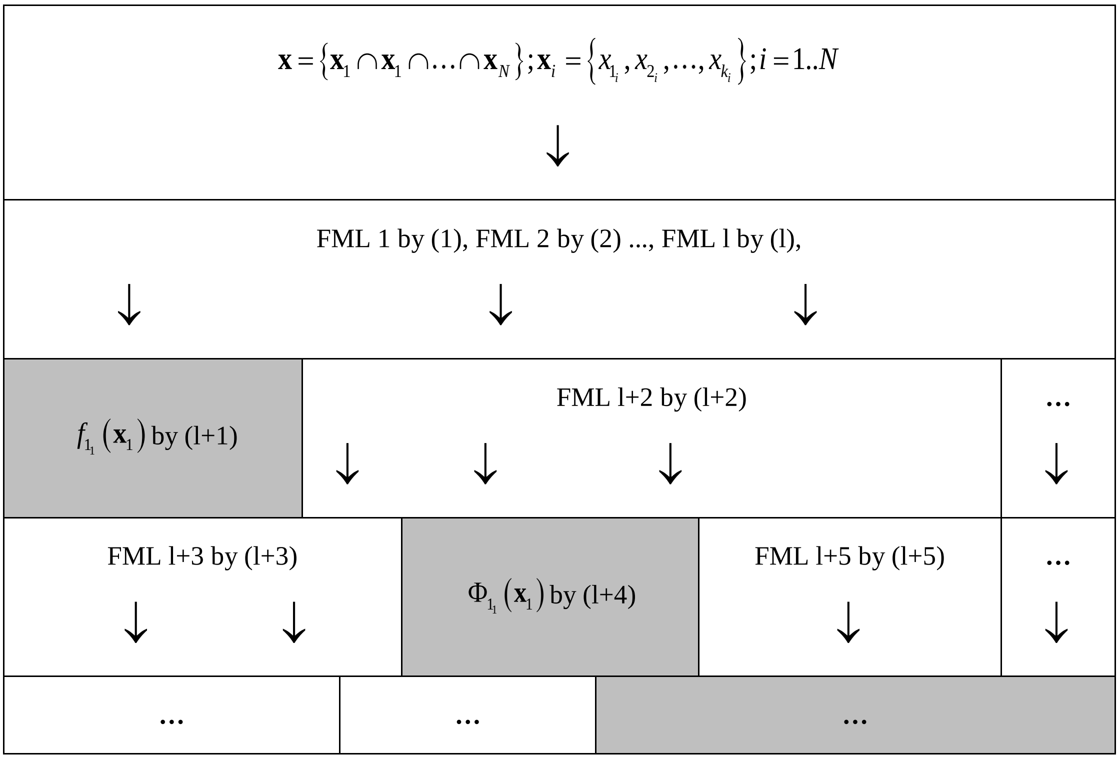


Figure 4. Multi-objective mathematical model formation

To build the model in Figure 4, it needs to use a routing table, in which determination order of constraints and objective functions is top-down, as shown in Figure 5, from the initial parameter vector **x**, (FML)$_i$ can be defined by formula or calculation method (i), which has been already considered in the model. According to routing table (Figure 5), calculation is carried out and shifted to next step at the white cell, while at the gray cell the calculation of function is stopped. The use of routing table is also an effective manner to describe multi-objective mathematical models in computing programs like MATLAB®, MAPLE®, or MATHEMATICA®. When the model contains a large amount of control parameters, constraints and objective functions, routing table also eliminates overlapping calculation, thus it is more convenient to manage the model.



$$\mathbf{x} = \left\{\mathbf{x}_1 \cap \mathbf{x}_1 \cap \ldots \cap \mathbf{x}_N\right\}; \mathbf{x}_i = \left\{x_{1_i}, x_{2_i}, \ldots, x_{k_i}\right\}; i = 1..N$$

↓

FML 1 by (1), FML 2 by (2) ..., FML l by (l),

↓ ↓ ↓

$f_{1_1}(\mathbf{x}_1)$ by (l+1) | FML l+2 by (l+2) ↓ ↓ ↓ | … ↓

FML l+3 by (l+3) ↓ ↓ | $\Phi_{1_1}(\mathbf{x}_1)$ by (l+4) | FML l+5 by (l+5) ↓ | … ↓

… | … | …

↓	↓	
$\Phi_{n_N}\left(\mathbf{x}_i\right)$ by (s)		

Figure 5. Routing table used for determination of mathematical model in design procedure

(3) Multi-objective mathematical model solution

In PAMMS, visual interactive analysis tool or VIAT is used [27-31]. VIAT is a very useful tool in determination of suitable solutions, or even Pareto. The idea of VIAT is described in Figure 6. VIAT is also considered as a sharing space, where the experts can work and communicate one to another. Thank to various optimization algorithm embeded inside, VIAT allows to perform various tasks in solving multi-objective mathematical model that described in details in the work [13]. As soon as, there is a mutually-agreed solution among experts, design engineers can conduct the design and modelling in computer-aid design program on the basis of the resultant parameters, then carry on manufacture successively.

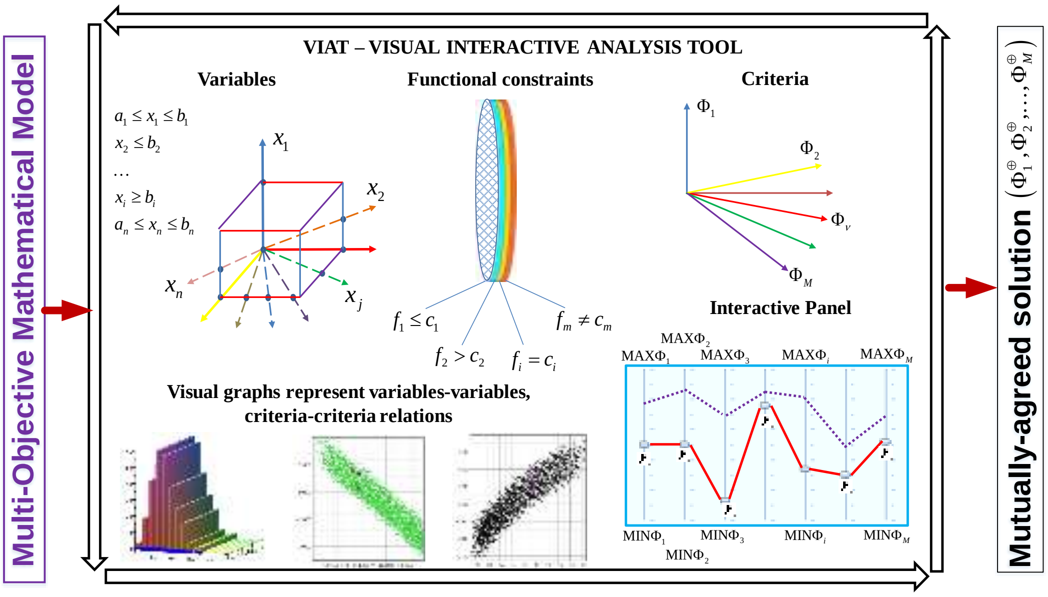
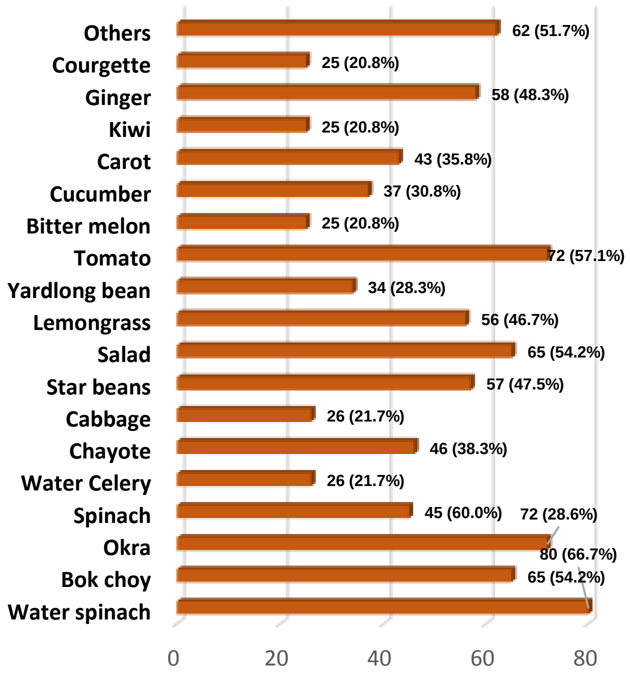
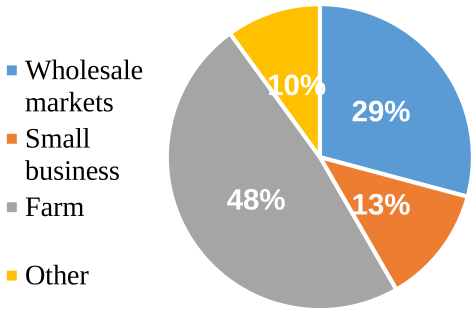


Figure 6. Illustrative idea of VIAT

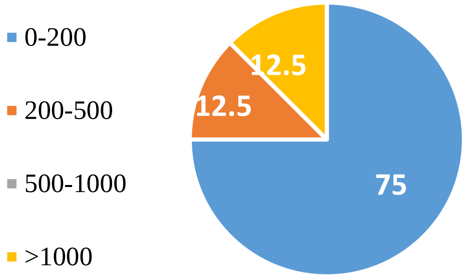
APPLICATION OF PAMMS FOR DESIGN OF AN INNOVATIVE FRUIT AND VEGETABLE WASHER

In this paper, PAMMS is used for the design of an innovative fruit and vegetable washer in particular production contexts. Based on the demand of this machine, PAMMS starts from the market survey at several places in Vietnam, as described in Figure 7.



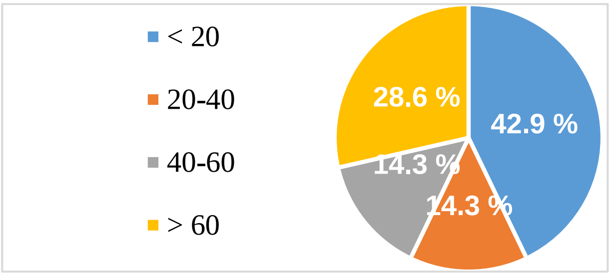


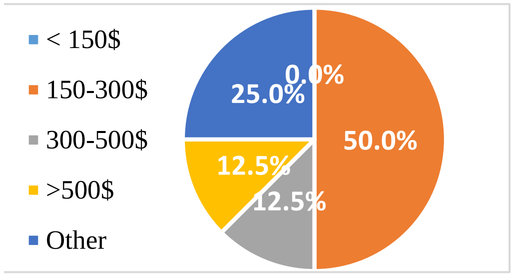
b. Origin of fruit/vegetable



a. Common fruit/vegetable and percent of usage frequency

c. Average daily consumption of fruit/vegetable involved (kg)





d. Time taking to wash 10 kg of fruit/vegetable

e. Expenditure for fruit/vegetable washing

Figure 7. Summary of maket survey at the locations, where fruit and vegetable washing is involved in Vietnam

From the survey, several informations are derived: (i) Tropical fruit/vegetables (Figure 7.a), which are purchased from the farm and/or wholesale market (Figure 7.b), often accompany with mud or soil. Thus, the current market-available washers like the ones with Ozone involvement and/or ultra-violet treatment are not the best solution for soil/mud removal. In fact, a mechanical washer seems to be the most effective one for tropical fruit/vegetables; (ii) Based on the daily consumption (Figure 7.c), the average capacity of the desired washer is around 500 kg per day; (iii) In term of time consumption and expenditure for fruit/vegetable washing, as shown in Figure 7.d and Figure 7.e respectively, the washing productivity is 10 kg every 10 minutes, and ultility consumption is less than 150 USD per month; (iv) In addition, the purchase price of the desired washer should be less than 5000 USD per unit.

In order to achieve the goal, the function-mean tree "Why – How – What" for the fruit/vegetable washer is built, as it can be observed in Figure 8. From this tree WHW, the main parts of the desired washer are formed. It is important to note that the key point of the washer is an innovative mechanism of drum motion that slide-crank mechanism involves spring for horizontal motion and cardan-joint for rotational motion [32], hence, the mathermatical model focuses mainly on these issues.

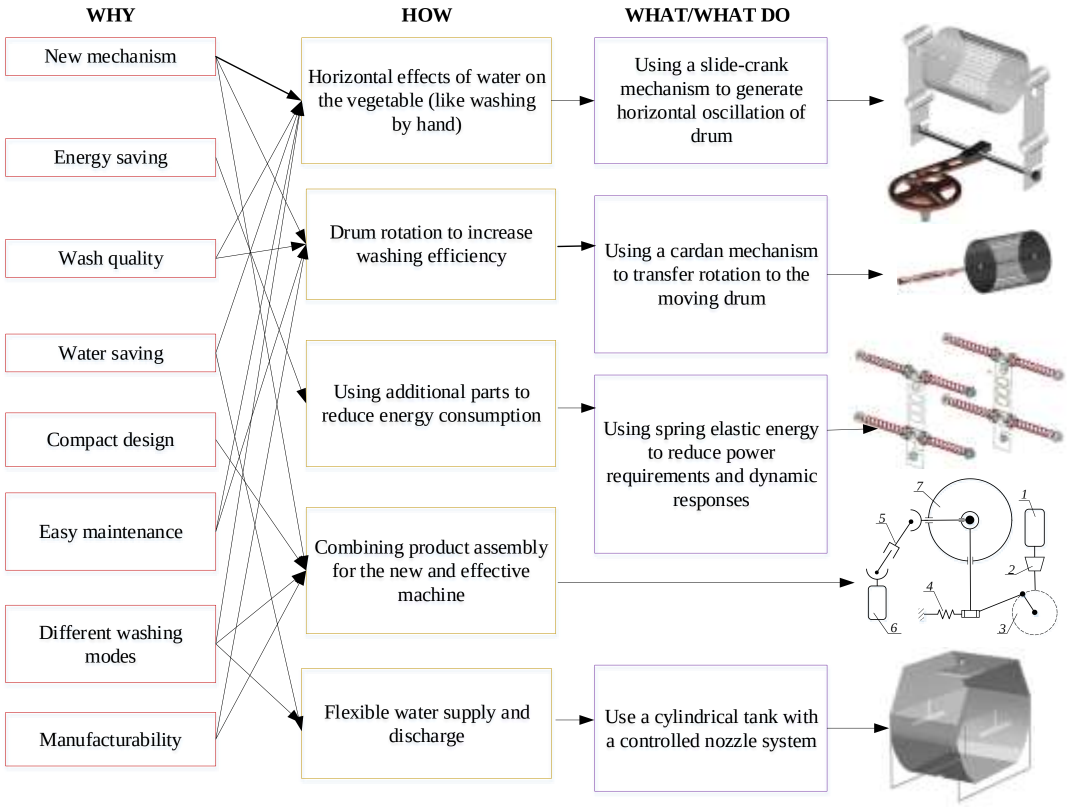


Figure 8. Function-mean tree "Why – How – What"

The quality criteria that set for the fruit/vegetable washer include washing quality, consumption of water and electricity, vibration level (life service and noise), and purchase price. To obtain the complete model with the mentioned requirements, it needs to take into account several limitations such as manufacturing technology, strength/fatigue limits of material, as well as scales. Information on geometrical scale, dynamic and kinematic parameters is also considered in the process of ROP development. Figure 9 provides diagram ROP of the desired washer [33]. By using this diagram, it is possible to conduct all of parameters, correlation among requirements and objects. Depeding upon each production context, the corresponding mathematical model is formed. In this work, two design scenarios are considered as follows:

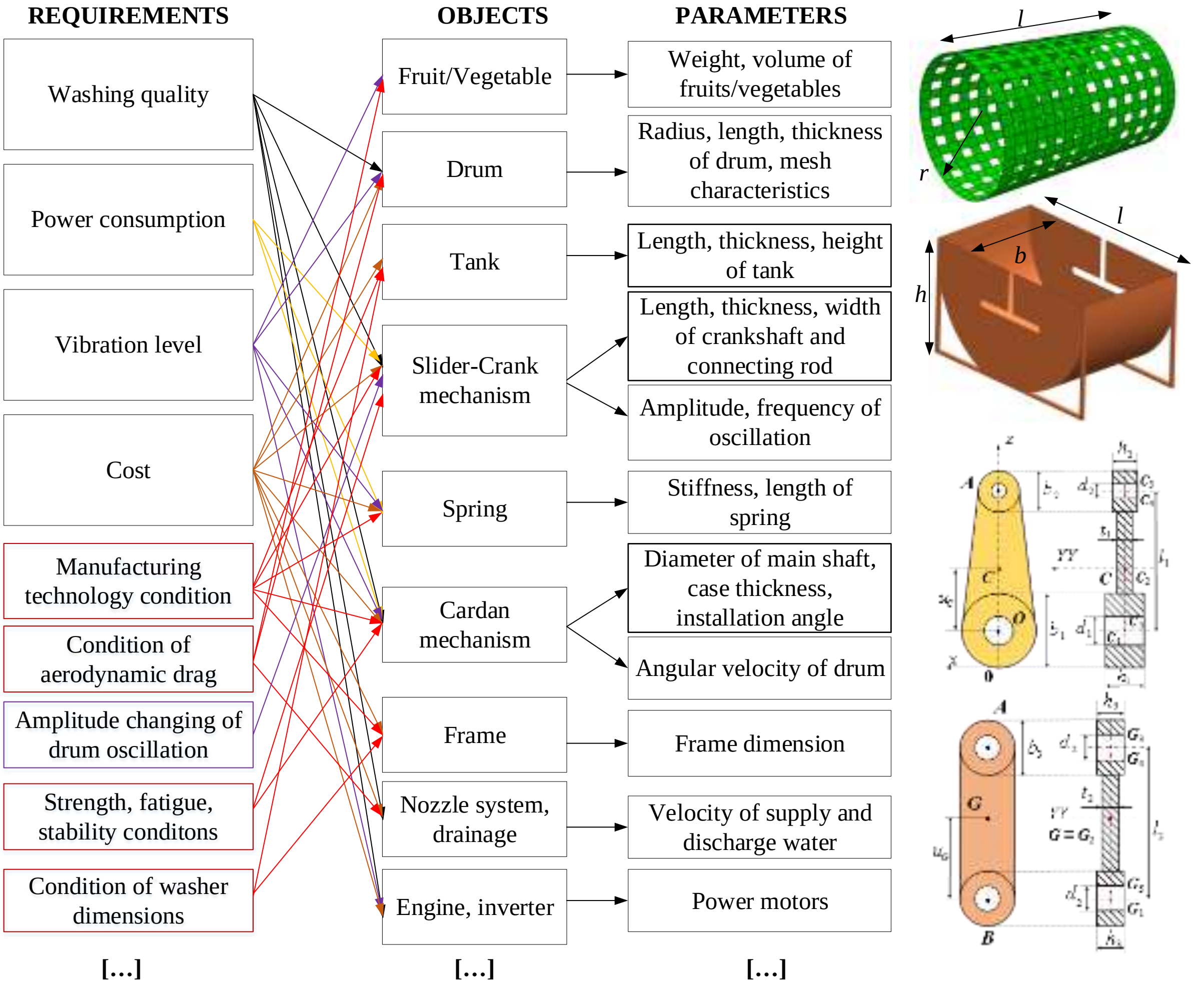


Figure 9. Diagram ROP of washer

Scenario 1: Supposedly, there is a situation when a particular manufacturer concentrate purposely on quality and productivity of a new model washer regardless of budget for it. In this case, the experts need to examine all of conditions and technical requirements. Eventually, the design procedure for this scenario is obtained, as described in Figure 10. Based on this, a multi-objective mathematical model is developed by mean of routing table in Figure 11. The model consists of four objective functions (**Φ_1-Φ_4**) and eight constraints (**f_1-f_8**) with nine initial parameters (**α_1-α_9**). Indeed, VIAT has supported to find out the solution [34]. Once valid design parameters (**α_1-α_9**) is defined, PAMMS stops. Next step is verification and manufacturing. The prototype of the desired fruit/vegetable washer in this scenario is illustrated in Figure 12.

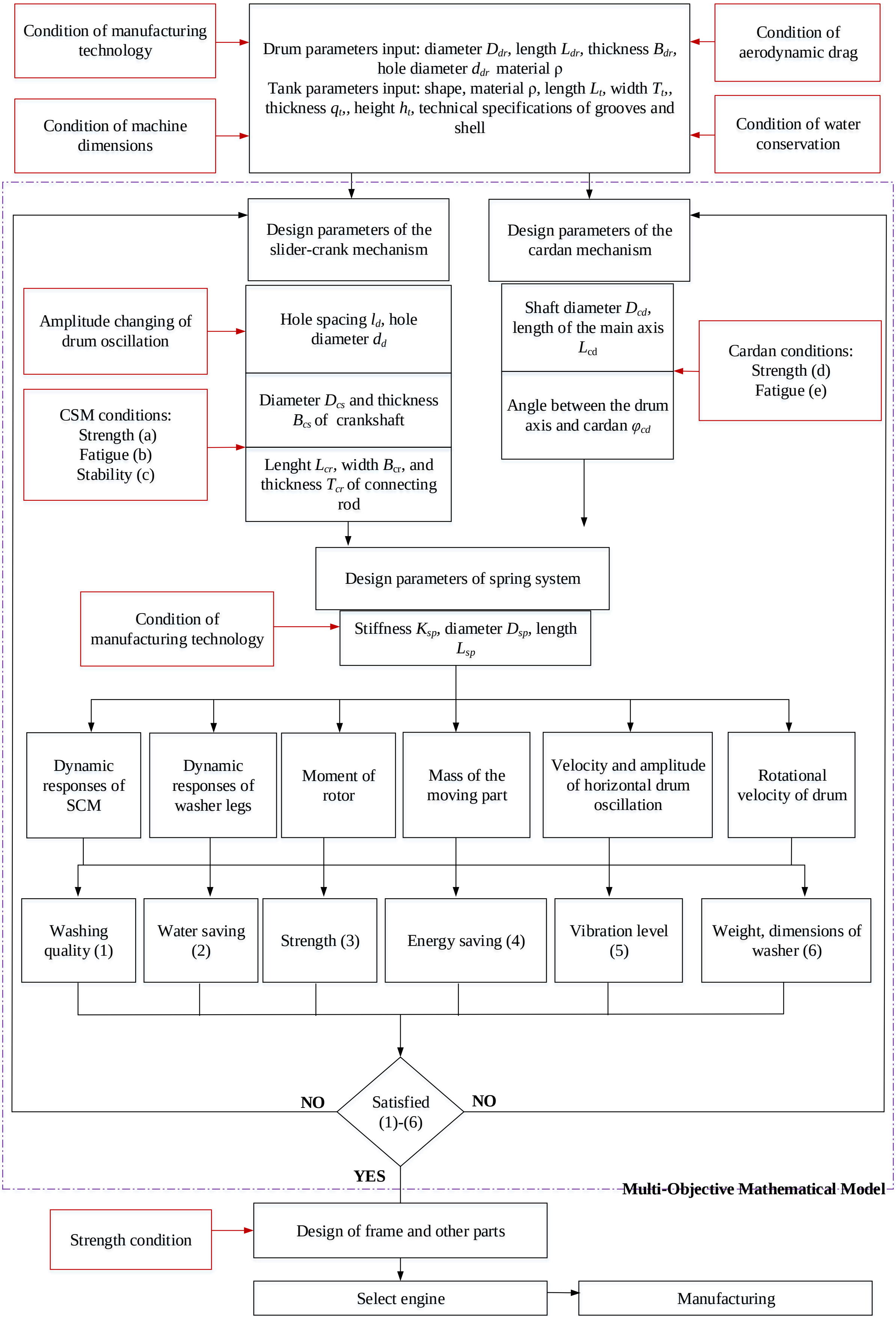


Figure 10. Design procedure in a particular production context - Scenario 1

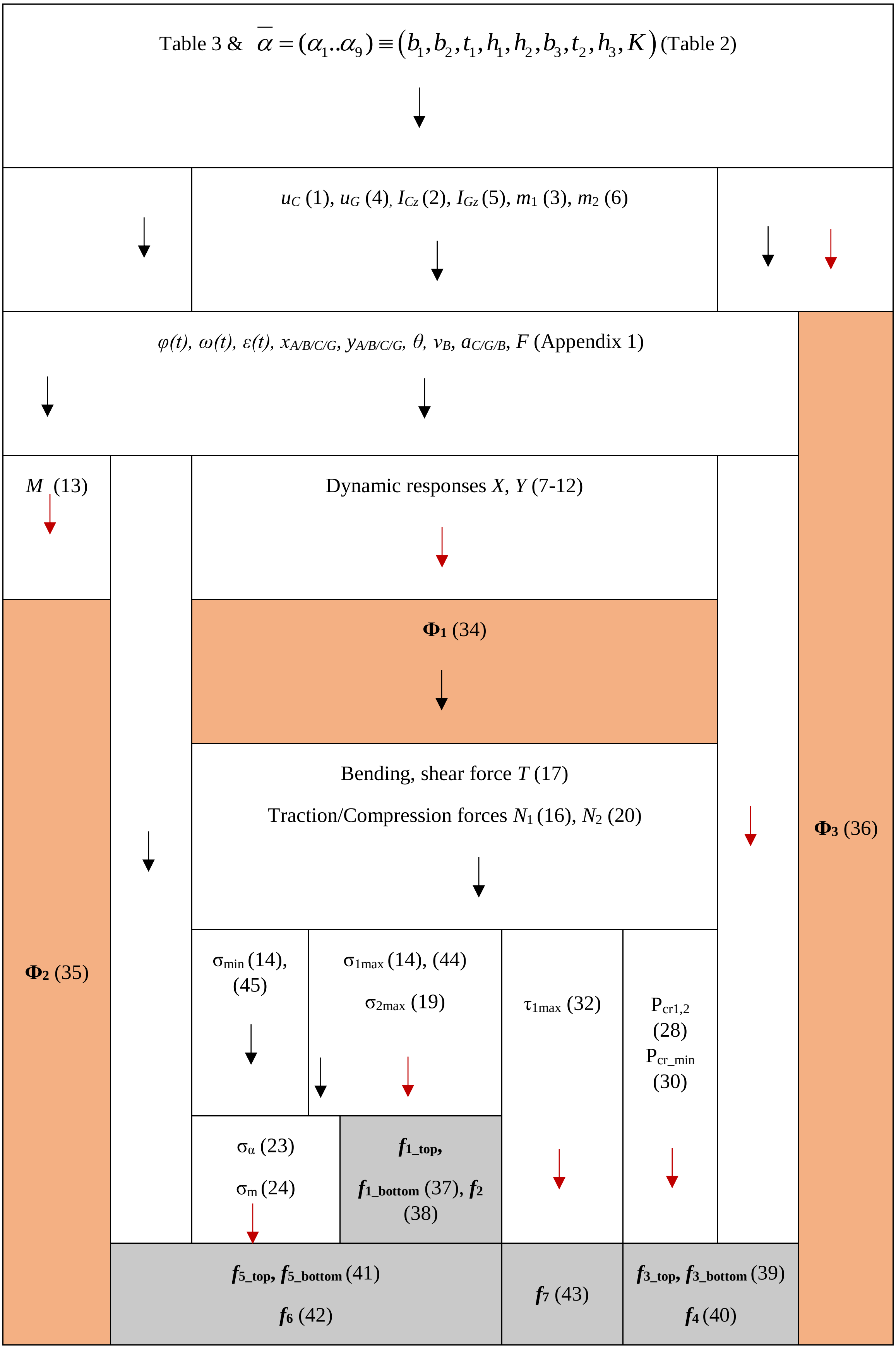


Figure 11. Routing table of mathematical model according to Scenario 1

Figure 12. 3D model (left) and prototype (right) according to Scenario 1

Scenario 2: Budget for the washer is the biggest challenge in this scenario. Thus, it needs to optimize the production cost and a small-size washer is a target. To do that, several parts of the washer are modified; the crankshaft of slide-crank mechanism is adjusted from a disc to a bar; rotary motor for the slide-crank mechanism is mounted under the drum; cardan connecting-rod is abolished; the rotary motor for drum is mounted directly in the rotary shaft and move together with the drum. The design model and prototype of the washer in this scenario is demonstrated in Figure 13.

Figure 13. 3D model (left) and prototype (right) according to Scenario 2

CONCLUSION

Procedure for Automation of Mathematical Modeling and Solution or PAMMS was proposed in this paper. The key point of PAMMS is to support engineer in building and solving the multi-objective mathematical model in different production contexts, which is inherently the most complex process in dealing with design of mechanical system. Besides, PAMMS was implemented for the design of an innovative fruit and vegetable washer. At two particular production scenarios, the corresponding models of the washers were designed, processed and manufactured properly. This pointed out that PAMMS is a truly-effective tool for design and development of mechanical system in general.

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