M. KEMAL TANKUT

MODELLING AND OPTIMIZATION OF HARNESS DESIGN AND COST ANALYSIS USING SOFTWARE TOOLS

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
ATILIM UNIVERSITY

MEHMET KEMAL TANKUT

A MASTER OF SCIENCE
IN
THE DEPARTMENT OF MECHANICAL ENGINEERING

JULY 2021

ATILIM UNIVERSITY

MODELLING AND OPTIMIZATION OF HARNESS DESIGN AND COST ANALYSIS USING SOFTWARE TOOLS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
ATILIM UNIVERSITY

BY

MEHMET KEMAL TANKUT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE IN THE DEPARTMENT OF
MECHANICAL ENGINEERING

JULY 2021

Approval of the Graduate School of Natural and Applied Sciences,Atilim University.

_____

Prof. Dr. Ender
Keskinkılıç
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of **Master of Science in Mechanical Engineering, Atılım University**.

_____

Prof. Dr. Sadık Engin
Kılıç
Head of Department

This is to certify that we have read the thesis MODELLING AND OPTIMIZATION OF HARNESS DESIGN AND COST ANALYSIS USING SOFTWARE TOOLS submitted by MEHMET KEMAL TANKUT and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science-Mechanical Engineering.

_____	_____
Prof. Dr. Ali Kara Co-Supervisor	Asst. Prof. Dr. Bahram Lotfi Sadigh Supervisor

Assc. Prof. Dr. Bünyamin Tamyürek
Electrical Electronic Eng. Department, Gazi University_____

Asst. Prof. Dr. Bahram Lotfi Sadigh
Manufacturing Eng. Department, Atılım University _____

Prof. Dr. Ali Kara
Electrical Electronic Eng. Department, Gazi University_____

Asst. Prof. Dr. Besim Baranoğlu
Manufacturing Eng. Department, Atılım University _____

Asst. Prof. Dr. Hakan Kalkan
Manufacturing Eng. Department, Atılım University _____

Date: *13.07.2021*

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : M. Kemal Tankut

Signature :

ABSTRACT

MODELLING AND OPTIMIZATION OF HARNESS DESIGN AND COST ANALYSIS USING SOFTWARE TOOLS

Tankut, Mehmet Kemal

Master of Science, Department of Mechanical Engineering

Supervisor : Asst. Prof. Dr. Bahram Lotfisadigh

Co-Supervisor : Prof. Dr. Ali Kara

July 2021, 47 pages

A harness is a cable web or an assembly of cables that transmits electrical power, signals, or information between two or multiple sources. It also may have some other subcomponents such as connectors, backshells, wires, boots, transitions, shields, jackets, and splices. Since a harness may consist of various materials and subcomponents, determining required materials is critical in the harness design and production process. The selection of appropriate components requires an excessive amount of time to browse through standards and datasheets, therefore. Time losses are depending heavily on the designer's experience level and complexity of the ordered harness. In this research, to reduce time losses during harness design and meanwhile reduce the risk of error in component selection software is developed. This study encapsulates the impacts and results of such an attempt to improve harness design process considering harness complexity, user experience. According to experimental results, consumed time on projects per month for each designer is calculated and a cost model developed. Finally, the contribution of prepared software is evaluated and results show that application of this software in the design and development process of harness regardless of harness complexity and user experience is beneficial.

Keywords: Wire Harness, Harness Design, Design Automation Software, Designer Experience Comparison, Harness Size Comparison, Harness Cost Model.

ÖZ

YAZILIM ARAÇLARI KULLANARAK KABLAJ TASARIMI VE MALİYET ANALİZİNİN MODELLENMESİ VE OPTİMİZASYONU

Tankut, Mehmet Kemal
Yüksek Lisans, Makine Mühendisliği Bölümü
Tez Yöneticisi : Dr. Bahram Lotfisadigh
Ortak Tez Yöneticisi : Prof. Dr. Ali Kara

Temmuz 2021, 47 sayfa

Bir kablaj elektriksel gücü, sinyali veya veriyi iki veya daha fazla kaynak arasında ileten kablo ağı veya kablo montajlarına denir. Bir kablaj aynı zamanda, konnektörleri, arkalıkları, iletken telleri, koruyucu kılıfları, branşmanları, metal örgüleri, kablo ceketlerini ve birleştirici kılıfları gibi bazı alt bileşenler içerebilir. Bir kablaj çeşitli materyal ve alt bileşen içerebildiği için gerekli malzemelerin kablaj tasarımı ve imalatı sürecinde belirlenmesi kritiktir. Bu nedenle, uygun bileşenlerin seçimi, standartlar ve veri sayfalarına göz atmak için çok fazla zaman gerektirir. Zaman kayıpları, büyük ölçüde tasarımcıların deneyim düzeyine ve istenilen kablajın karmaşıklığına bağlıdır. Bu araştırmada, kablo demeti tasarımı sırasında zaman kayıplarını azaltmak ve bu arada bileşen seçimlerinde hata riskini azaltmak için yazılım geliştirilmiştir. Bu çalışma, kablaj karmaşıklığı ve tasarımcı tecrübesi göz önünde bulundurularak, kablaj tasarım sürecini geliştirmeye yönelik böyle bir girişimin etkilerini ve sonuçlarını özetlemektedir. Deneysel sonuçlara göre, her tasarımcı için projelerde aylık harcanan zaman hesaplanmış ve bir maliyet modeli geliştirilmiştir. Son olarak, hazırlanan yazılımın katkısı değerlendirilmiş ve sonuçlar, bu yazılımın kablaj tasarım ve geliştirme sürecinde, kablaj karmaşıklığı ve kullanıcı deneyimi ne olursa olsun uygulanmasının faydalı olduğunu göstermektedir.

Anahtar Kelimeler: Kablaj, Kablaj Tasarımı, Tasarım Otomasyon Yazılımı, Tasarımcı Deneyimlerinin Kıyaslanması, Kablaj Maliyet Modeli.

Dedicated to my family, my best friends and my teachers who always help me.

ACKNOWLEDGMENTS

I would like to express my thanks to my supervisor Asst. Prof. Dr. Bahram Lotfisadigh and my co-supervisor Prof. Dr. Ali Kara for their guidance and belief in me. They helped me a lot at our meetings.

I shall also thank Prof. Dr. Engin Kılıç who is Head of the Department of Mechanical Engineering for allowing me to undertake this work.

Furthermore, I thank the members of TTAF Defense Company, Esra Güler, Mehmet Tosun, and Okan Güneş for helping me in the experiment.

The supports of the general manager of TTAF Defense, Mr. Ergün İşgör is also acknowledged.

Finally, my most thanks to my parents, they always support my works, especially my mother even helped me so much for preparing software, she did most of the coding.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF SYMBOLS/ABBREVIATIONS

δ	Total accomplished project
T	One-month working period
w_{ij}	Consumed time for a specific type of project
s_i	The salary of designers
R_i^{NH}	The total risk cost factor of each error group (No HMS)
R_i^H	The total risk cost factor of each error group (HMS)
$r_{ms_i}^H$	The risk cost value of material selection error gorup
$r_{c_i}^H$	The risk cost value of calculation error gorup
$r_{d_i}^H$	The risk cost value of documentation error gorup
$p_{ms_i}^H$	Risk probability for material selection
$p_{d_i}^H$	Risk probability for documentation
$p_{c_i}^H$	Risk probability for documentation
K_{ij}	The number of completed projects of ant designer (No HMS)
L_{ij}	The number of completed projects of ant designer (HMS)
y_{ij}^{NH}	Total risk cost of all projects (No HMS)
y_{ij}^H	Total risk cost of all projects (HMS)
q_j	The number of connectors
c_i^{NH}	Total monthly cost (No HMS)
c_i^H	Total monthly cost (HMS)
P_{ij}^{NH}	The cost of designer per project (No HMS)
P_{ij}^{NH}	The cost of designer per project (HMS)

CHAPTER 1

INTRODUCTION

Harnesses, cable webs, or cable assemblies containing cables, bundles, and some other electronic components are vastly used in different structures, devices, and systems to carry electrical power or data between sources. Since conductors carry electric signal, design, the appropriate material, and conductor selection for harness have great importance, it directly affects users' safety. Therefore, any mistake may result in dangerous and irrecoverable consequences. Meanwhile, the harness design process is a time-consuming, costly, and designer experience-based process. As the harness design process relies highly on the experience of the designer, therefore, unexpected errors may arise during this process. To deal with this problem in this study, new software is developed to reduce the necessity for user experience, eliminate the human error factor and consequently decrease design and manufacturing process costs. İn this study, the effects of applying developed software on the harness design process in terms of time, quality, and cost are analyzed and discussed.

Researches about harness in literature are mostly focused on manufacturing problems such as; ergonomic problems during harness assembly, wire manufacturing, assembly problems and etc. In manufacturing, usually, the methods are considered and compared with manual, semiautomatic, automatic, and robotized assembly systems. For instance, Aguirre and Raucent have studied the economic performance of automated, semi-automated, and manual assembly of harness production lines [1]. Another study which is conducted recently by Heisler et al. shows an improvement in the efficiency of harness production when a specifically designed robotic system is implemented during harness assembly [2]. Pre-grouping is a name given Gao et al. to a method that is applied in the harness production process to save time and improve production efficiency. In this method wires

between two terminals are gathered to form a group before crimping or soldering of wires and contacts and create an electrical path between terminals [3]. Reduction of total process time, by using alternative manufacturing processes, or enhance the production processes' automation level is the main objective in most of the articles in the literature. However, some of them are considered on the efficiency of the harness itself by redesigning of harness or selection of alternative materials or components. For example, Villanueva Ray et al. investigated weight reduction in the automobile industry by applying a single cable solution instead of harnesses in cars and [4]. Del Pero et al. also conducted a study in the automotive industry to reduce the weight and consequently the fuel consumption of cars by the selection of alternative materials in harness design and production [5]. Another study carried out by Zhou et al. represents a method to simulate and predict the cable harness fatigue life in robots. The material property effect on harness fatigue life is simulated and predicted and based on this information the optimum material can be selected [6]. Out of manufacturing cost and time in harness area, studying of the harness production ergonomically is also mentioned in literature widely. The researchers determined the possible risks on the body during harness production, assembly, they built a wire harness conveyor line and this conveyor helped the operators to reduce joint reaction forces of up to 59% in the trunk, 69% in the shoulders [7]. There are other optimizations works on ergonomically manufacturing therefore, some researchers aimed to reduce low back pain (LBP), so they rearranged the two different assembly lines of a company, combined each line, and eliminated two material handling tasks, enriched the employees' jobs [8]. Another study in ergonomic working was carried out on risk determining between different departments in offices, and the R&D department was determined as the highest level of strain [9]. Researchers also examined to reduce spine loads, thus they evaluated two interventions such as a self-leveling pallet carousel and an adjustable card. When they combined each intervention, spine compression is reduced by 61% [10]. There are also a few kinds of research on design optimization as well. In some of these studies, the software is developed, that helped to select the most efficient electrical architecture via wire routing and sizing, and each study emphasized cost was reduced since wire paths were optimized [11-13]. Some researchers examined the possibility of a harness

design by using virtual reality, which was a good way to examine, categorize, and a wider range of design activities, and a better way to understand design methods in detail. Studies showed designing by VR is more efficient than traditional design methods. [14-15]. Beside of the design studies, some quality and test optimization study was also carried out on mating of female and male connectors. The quality process in the harness sector usually consists of mating female and male connectors with each other. Researchers aimed to measure tolerances of various cable connectors with maximum movement in mating operation. After obtaining tolerances, the mating process can be provided by the utilization of only pose control [16].

Few studies are conducted regarding design optimization, and almost there are no researches on the optimization of material selection in the design process. In design optimization studies, harness shapes and configurations are usually considered. İn this study, a design optimization study is carried out with and without the help of software selection of harness subcomponents called "Harness Material Selection (HMS)". Decreasing design completion time for each project, so reducing design cost per project is aimed.

This research shows the contribution of HMS software on harness design in terms of saved time and cost. Therefore an experimental design is organized that includes harness size, the experience of designers and, utilization of software.

1.1. Basic Sub-components of A Harness

Knowing basic information about harness subcomponents is mandatory before starting a project design. Each component has played a different role in a harness. The connector is electromechanical that connects cables and systems together and creates circuits. The task of an electrical connector is mainly disturbing power and current between two electrical parts and they are generally used in routers, mass storage devices and, airplanes [17]. A backshell is an accessory and rear part of the connector that connects metal braid of cable to the connector, metal braid can be terminated to the backshell [18]. A backshell is normally a separate section from the connector head, used to secure the end of the connector. Wires are usually copper

conductors (tin-plated for defense works) with different AWG. AWG is a unit that has an equivalent value in terms of mm and mm^2. Shields or metal braids are used to prevent EMI (electromagnetic interference) [19]. EMI is an undesired property in terms of smooth signal or power transfer. A jacket or a heat-shrinkable tube can be obtained from various plastic materials and it primarily serves to protect the cable during installation [20]. It is also used for extra insulation and preventing liquid leakage. Its hole diameter can shrink to the desired measure by a heat gun. Boots are similar to jackets, except their one end shrink on the jacket and the other end shrinks on the backshell. They protect the rear of the backshell. When boots are heated above 1350^C, they shrink down over the connector or backshell and cable, they also fix the shield that is terminated to the backshell. They protect against unwanted signal leakage and provides mechanical protection and strain relief [21]. Transitions are used for cable separation points and they are also called a connection of two or more cables [22]. They also have a similar purpose with jackets and boots. Splice and solder sleeves: These materials are used to bond for different size (AWG) conductors, or bond different numbers of conductors together. Another research shows that the large mechanical deformations in a splice improve connector performance remarkably [23]. Solder sleeves are mainly used to shield termination but sometimes they can be also used to bond wires together just like splices. A solder sleeve is a pre-installed pellet of solder with flux, it is heated and solder melts, so contact between wires is created [24].

1.2. Cable Assembly

A harness is also called a cable assembly and it may consist of any sub-components, mentioned in section 1.1, with any quantity. Figures 1.1 and 1.2 show a standard cable assembly. Firstly, wire paths are created, some of them are connected in the area of transition, or some of them are connected by a splice or solder, and transitions pass over wires, then the shield is shrined on the wire, then jacket shrinks on wires. Backshell settles down to connector, boot shrinks on backshell and on the jacket. Transitions which is passed over on wires are shrunk on jackets.

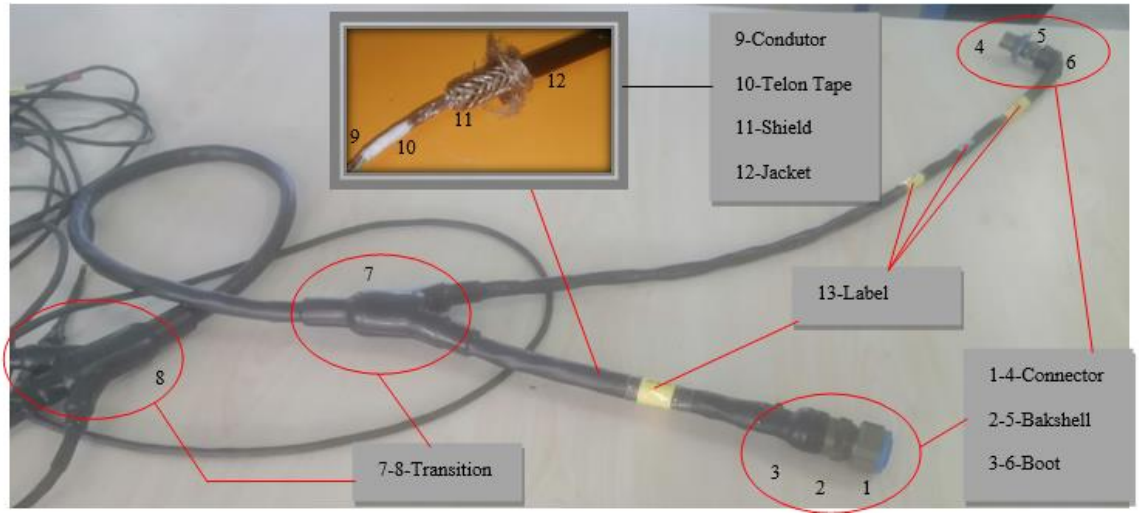


Figure 1.1 A cable assembly with its sub-components

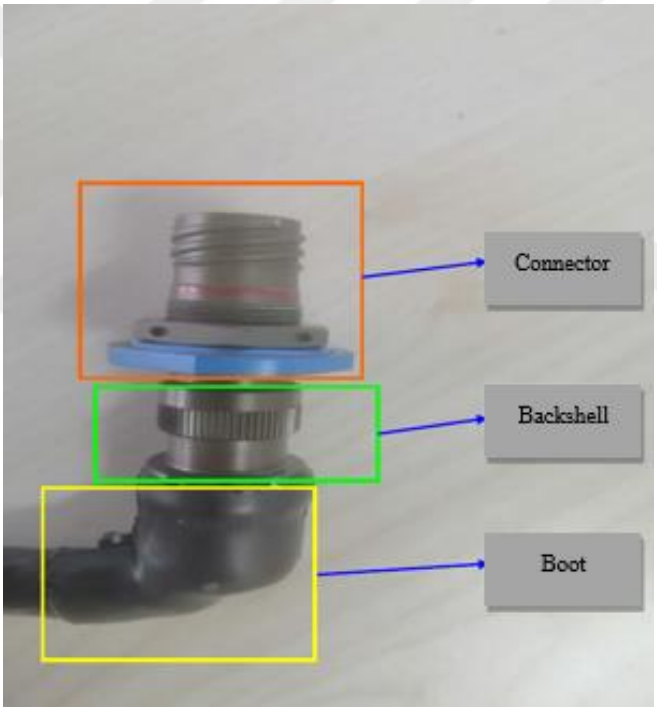


Figure 1.2 United connector, backshell and boot

CHAPTER 2

HARNESS ACTIVITY DIAGRAMS

Just like most of the engineering process, in harness design, general process activity and detailed design activity should be well known. The basics of work order to analyze the cost model of harness design are mentioned in section 2.1, and detailed harness design activities with and without HMS are mentioned in section 2.2.

2.1. General Cost Model Activity for Harness Design

Before creating a cost model, knowing harness design activities is essential. If one can know the activities, he or she also forecasts the risks of the design process. After risks are determined, a good cost model can be revealed. An example of work came from N.S. Ong, activity-based costing (ABC) is revealed [25]. This work shows us to needed steps for cost calculation (Figure 2.1).

Figure 2.1 Developing the activity-based cost model

In this study, the work order is quite similar to the ABC model. There are a total of 5 main steps shown below:

Steps:

1. **Identify activity requirements:** Corresponding material selection according to the customer data package.
2. **Identify cost drivers:** Designers' salary, designers' experience, number of the completed design, harness size.
3. **Develop cost flow model:** Developing HMS (Harness Material Selection Software), NHMS (No Harness Material Selection Software) matrixes.

4. **Collect cost driver data:** Assumptions, risks and, the result of experimental design.
5. **Calculate activity cost:** 1.5 years of the average cost determination for all conditions.

2.2. Harness Design Activity

According to system needs, customers create an electrical scheme that shows the routing of wires and the place of the connector or terminals. They determine the distance of systems or between connectors to create a simple draft after checking the configuration of the vehicle or structure. In the end, a data package is revealed. Figures 2.2, 2.3 and, Table 1 show what a data package includes.

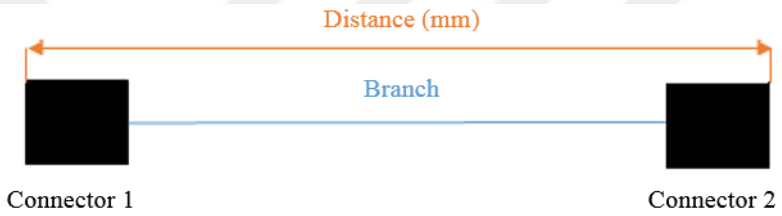


Figure 2.2 Drafting of a simple straight harness

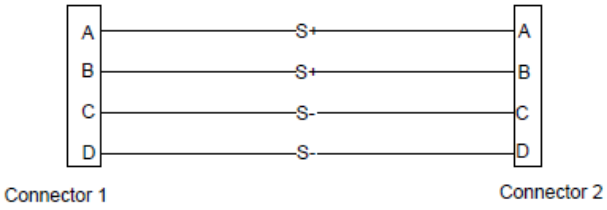


Figure 2.3 Electrical connection in branch

Table 2.1: Wire Indexes

Index	Name	Connector	Cavity	Connector	Cavity	Cable Cod	Color	Description
1	S+	D38999…	A	D38999…	A	M81044 …	White	20 AWG
2	S+	D38999…	B	D38999…	B	M81044 …	Black	20 AWG
3	S-	D38999…	C	D38999…	C	M81044 …	Red	20 AWG
4	S-	D38999…	D	D38999…	D	M81044 …	Blue	20 AWG

The customers' data package is accepted as the initial state of activity. Designers use data packages obtained from customer’s work. This part is very

important because it consists of lots of corresponding, suitable and, alternative material selection and searching work, which takes too much time for a designer. Since one of the main purposes is to decrease effort time on searching, the main difference should be graphed between manual and automation. Therefore, activity processes must be revealed. UML (Unified Modeling Language) is the outcome of the development of object-oriented technology and standardization of system's description and it can be used in describing any system [26]. Two different design activity diagram is prepared according to the rule of a book named as "Applying UML And Patterns [27]" such as HMS and NHMS.

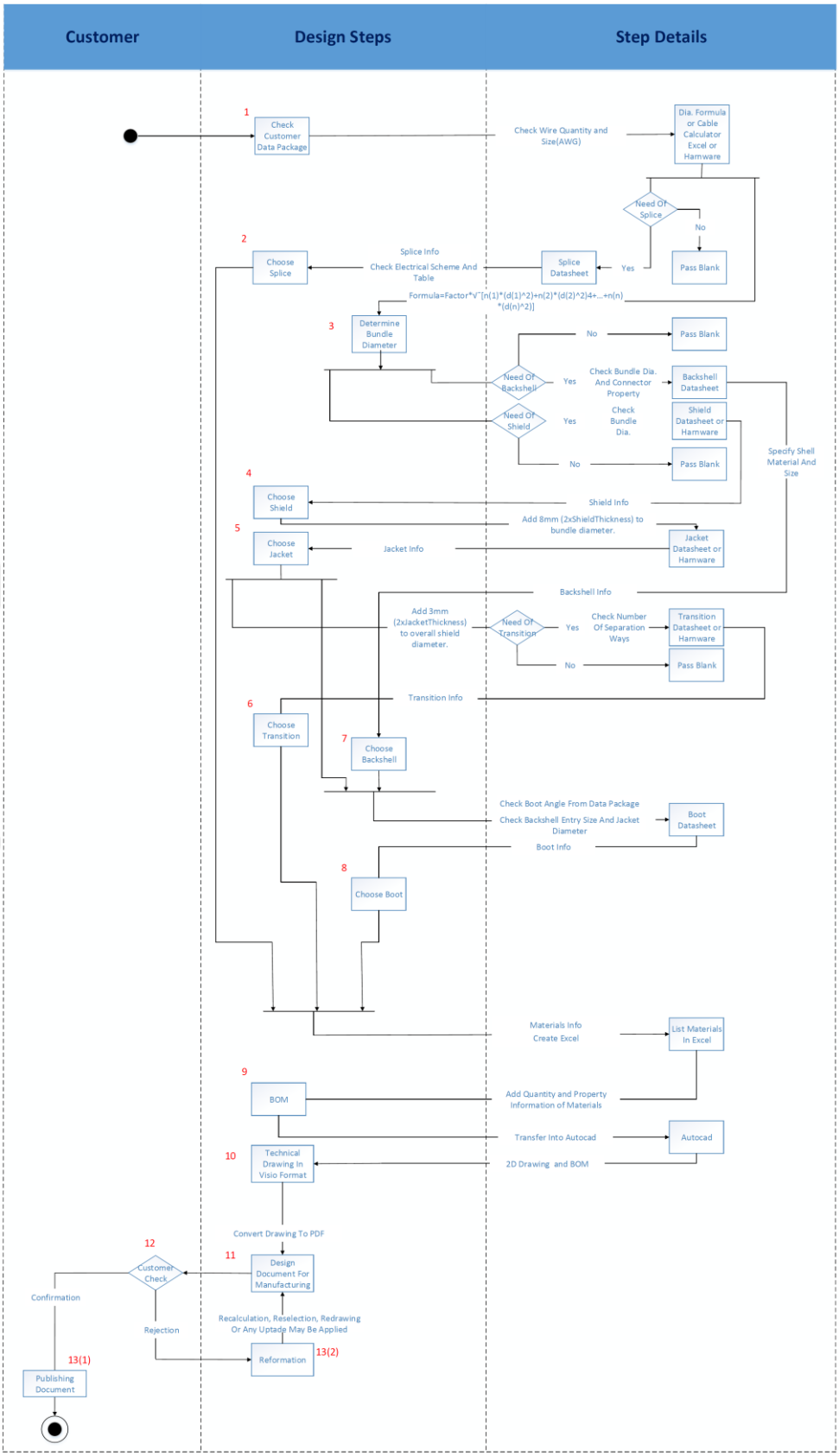
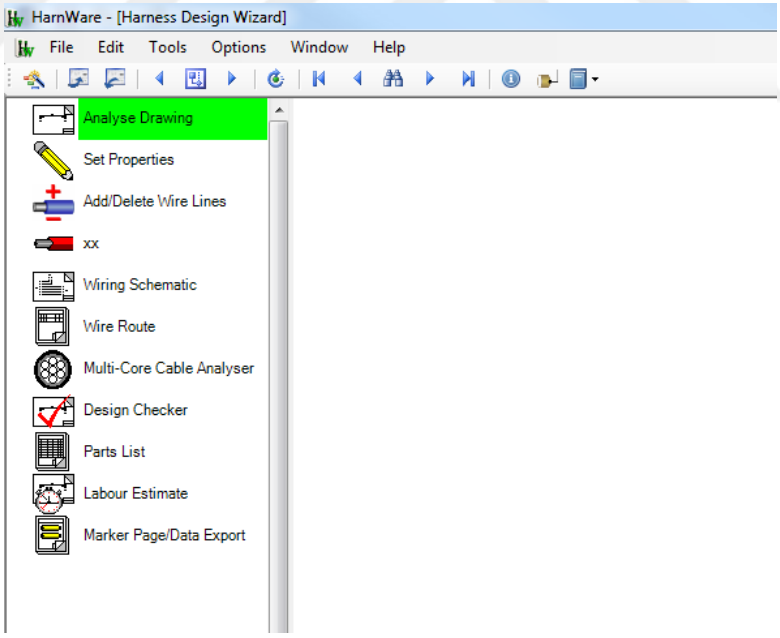


Figure 2.4 No HMS harness activity diagram

Steps:

1. **Data package checking:** Designers check materials and draft from data package prepared at the first phase. They check the number of wires for each branch and calculate the diameter of the wire bundle by using the standard formula (showed at step 3) or cable diameter calculator excel or Harnware (a most popular one). Figure 2.5 shows the interface of Harnware. In this step, splice need is also determined.

2. **Splice selection:** If there is no need for a splice, the designer can pass this step. But if the splice is required according to the data package, designers should check each wire diameter according to the data package need and splice inner diameter from the datasheet.
3. **Bundle diameter calculation:** In this step wire bundle diameter of each branch is calculated. Harnware is a common diameter calculation program, also it can determine TE Connectivity specific metal braid (shield) and jacket.



"Figure 2.5 Harnware interface showed in [28]"

Harnware uses the below rules and formula to calculate bundle diameter.

(Conductor Bundle)=Factor*$\sqrt{[}(1) * d(1)2 + n(2) * d(2)2 + \cdots + n(n) * d(n)2]$ [28]

d(1)…d(n) are diameters of each type of wire in the bundle.

N(1)…n(n) are the number of wires of the same diameter.

After determining conductor bundle diameter, shielding or jacketing may be added.

Final Outer Diameter= (Bundle Diameter)+2*(Shield Thickness)+2*(Jacket Thickness)

4. **Shield Selection:** If there is no need for the shield, the designer can pass this step. But if the shield is required, the designer should check the shield datasheet or can use Harnware to select a specific TE product. The main point is selected shield should shrink to wire bundle properly. The average shield thickness is usually 0,8mm.
5. **Jacket Selection:** The jacket is generally required sub-components for most cases. The designer should check the datasheet or can use the Harnware to select a specific TE product. The selected jacket should shrink on the overall shield properly. Jacket thickness may show variability for the selected one but on average its thickness can be accepted as 3mm.
6. **Backshell selection:** Backshells are important parts for protecting wire in connector socket or pin and termination of shields. Some connectors can be self-shelled but in the defense sector, circular connectors are mostly preferred, and they manufactured as separated from the backshell. Therefore a suitable backshell selection is needed by datasheet checking. Backshells' front side's dimension should be suitable for the connector from the data package and the back dimension should be bigger than the jacket diameter.
7. **Transition selection:** If there is no need for transition, the designer can pass this step. But if a transition is needed, its type should be determined first. It can be T shape, Y shape, 45^0 shapes, etc. Type is usually specified in the data package. The selected transition should shrink to the overall jacket diameter. Therefore designers should do datasheet research.
8. **Boot Selection:** Boots are also important parts to prevent cables from dust and water leakage. Just like transition, their shape may show variability such as straight, 45^0, 90^0, etc. Type is usually specified in the data package. The

selected boot should shrink on the backshell's rear and on the overall jacket diameter. Therefore designers should do datasheet research.

9. **Creating Bill Of Material (BOM):** After determined all corresponding or alternative materials, a BOM is created in excel form.
10. **Technical Drawing:** An understandable 2D drawing is created on Autocad, and created BOM in excel format is transferred to Autocad Drawing. After that, all drawing with BOM is converted to Visio format and technical drawing makeup is done on Visio.
11. **Finalizing:** After makeup is completed, the drawing is converted to PDF and becomes a document. Design is ready for customer check.
12. **Customer check:** Customers realizes detailed check and decide if the document needs some reformation or it is suitable for manufacturing.
13. **Confirmation or Reformation:** If reformation is decided, previous steps may be observed again or some small corrections might be sufficient. This loop continues until the confirmation. After confirmation, the document is sent to manufacturing.

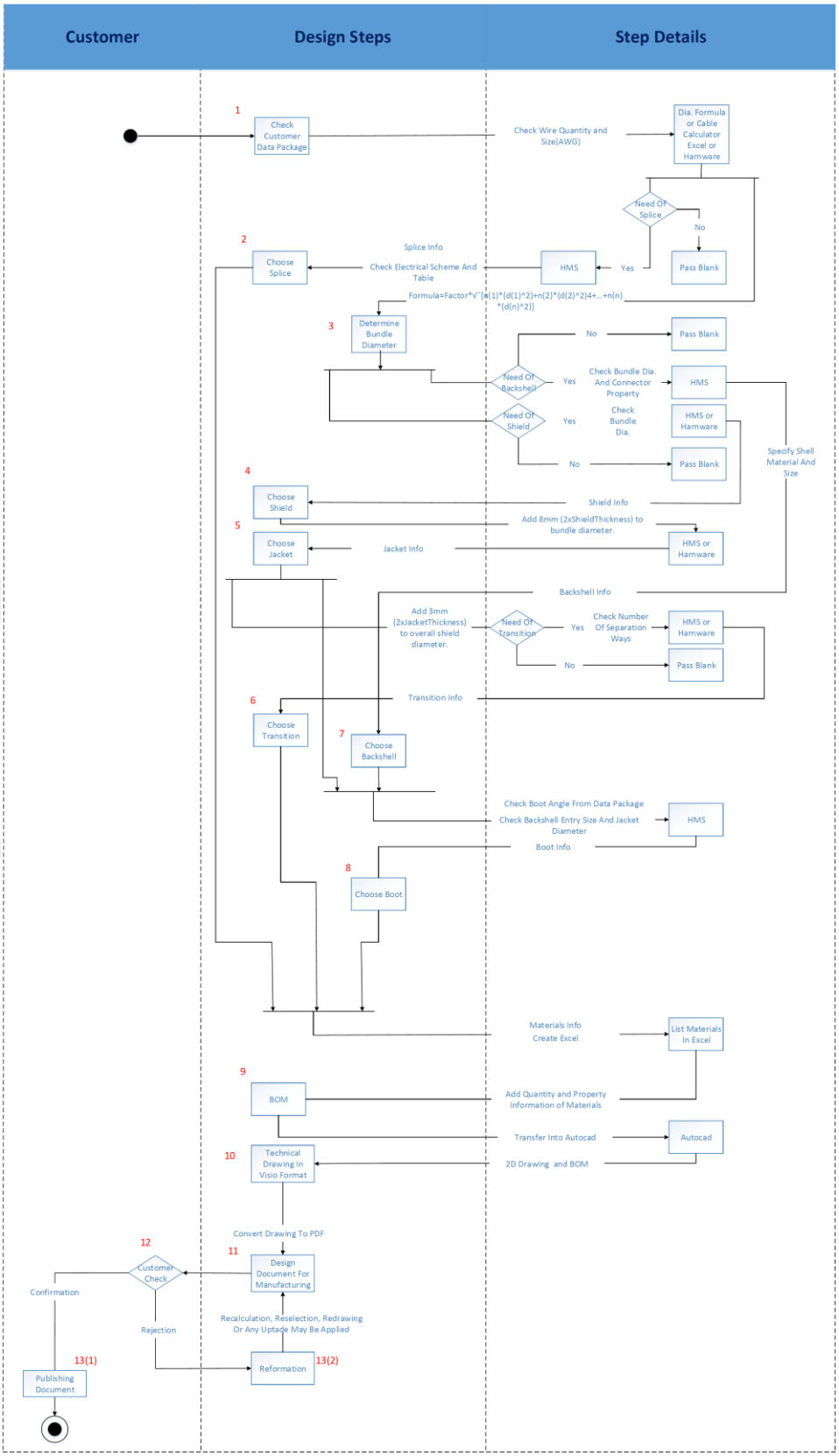


Figure 2.6 HMS harness activity diagram

For the HMS diagram, steps 9, 10, 11, and 12 are completely the same but for other steps, there is no need for datasheet researches anymore. Instead of datasheet research, known data is entered into HMS Software, and it determines suitable materials quickly. This is a very comfortable thing for designers since they don't have to lose so much time anymore for searching each different sub-components.

2.3. Harness Design Example

For a better understanding of the design process, let's consider a simple example. The data package comes from the customer. Actually data packages are prepared by system engineers, who are working on customers' company, according to vehicle or structure needs. In this example, the customer is a defense factory.

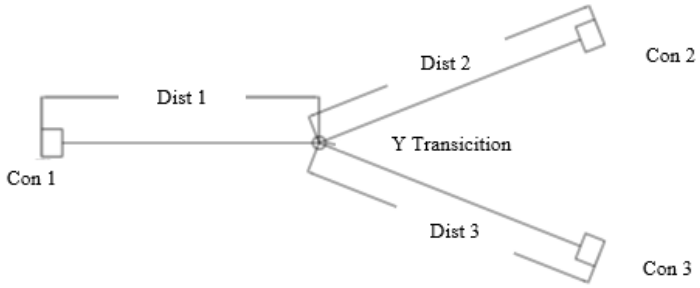


Figure 2.7 Data package 2D drafting

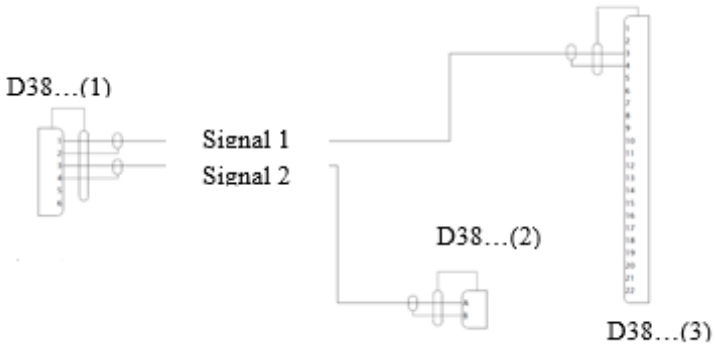


Figure 2.8. Data package electrical connection scheme

Table 2.2: Data Package Wire List

Harness Code									
Index	Name	Con.	Cavity	Con.	Cavity	Part N.	Color	Size	Group
1	Signal 1	C 1	1	C2	3	M….	….	….	Wire
2	Signal 2	C 1	3	C3	A	M….	….	….	Wire

A simple data package of a harness is shown in Figure 9, Figure 10, and Table 2.2. According to the given connectors, scheme, and wire information, designers can select suitable required materials and prepare technical drawings from the draft.

An example of completed BOM and the 2D technical drawing is showed in Figure 2.9 and Figure 2.10. The main document that is shared with manufacturing, should consist of BOM, 2D technical drawing, electrical schema, and index table from the data package.

S03...	28	Solder Sleeve	x piece	-
D-436...	27	Crimp Splice	x piece	-
60-40...	26	Tinned Copper	x gram	-
BIND W...	25	Copper Wire	x meter	-
TEFLON B...	24	Teflon Band	x meter	-
S1...	23	Adhesive	x gram	-
LOC...	22	Thread Locker	x gram	-
BM...	21	Label	x piece	-
RT...(2)	20	Label	x meter	-
RT...(1)	19	Label	x meter	-
TMS...(2)	18	Label	x piece	-
TMS...(1)	17	Label	x piece	-
382A...	16	Branch	x piece	-
222K...	15	Boot	x piece	-
202K...	14	Boot	x piece	-
DR...(2)	13	Jacket	x meter	-
DR...(1)	12	Jacket	x meter	-
RAY...(2)	11	Metal Braid	x meter	-
RAY...(1)	10	Metal Braid	x meter	-
M81...(2)	9	Wire	x meter	-
M81...(1)	8	Wire	x meter	-
UPT	7	Wire	x meter	-
91H1...(3)	6	Backshell	x piece	-
91H1...(2)	5	Backshell	x piece	-
91H1...(1)	4	Backshell	x piece	-
D38...(3)	3	Connector	x piece	-
D38...(2)	2	Connector	x piece	-
D38...(1)	1	Connector	x piece	-
MATERIAL NO	POSE	DESCRIPTION	QUANTITY	ZONE
Material List				

Figure 2.9 BOM of a document

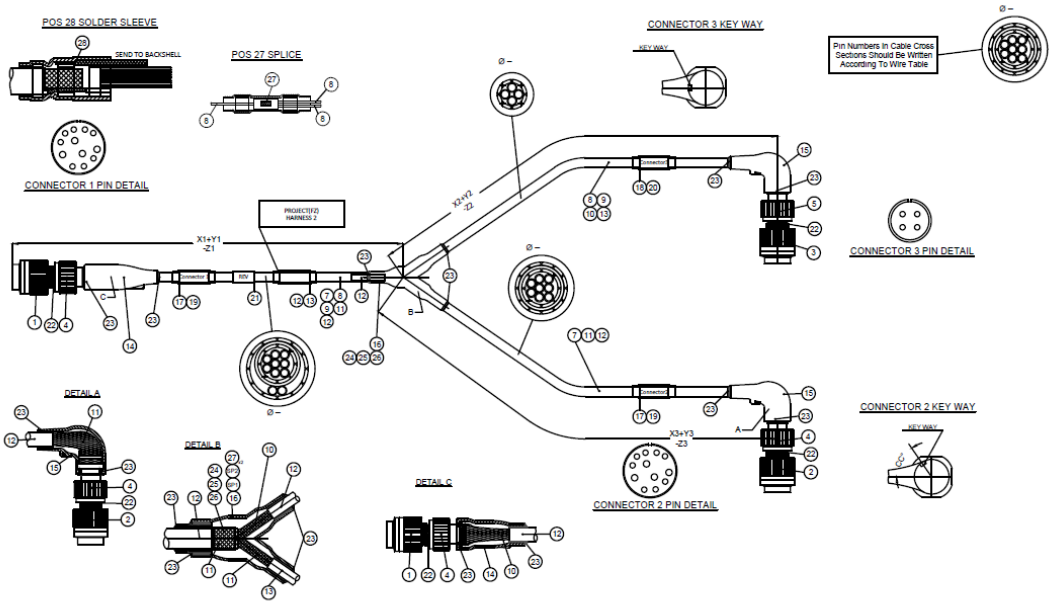


Figure 2.10 Technical drawing

CHAPTER 3

PROPOSED MODELS

In this report, the results of an experiment which is carried to study the effects of software application in harness design and development process duration and costs are illustrated. Considering the aforementioned harness development process properties, some evaluation factors are defined and used in this research. These factors are harness complexity, designers' experience, and utilization of software. The first factor is harness complexity that is the size of the harness. Complexity increases as harness size increases. A bigger harness requires more effort and the design period is longer. Designers' experience is the second factor. The experiment measures the performance difference between experienced and beginner designers in terms of design completion time. And the last factor is the utilization of software. Traditional manual harness design and development methods and automated methods with the use of HMS software are compared in this experiment.

This report also presents a cost model that includes some factors such as the salary of the designers, mistake risks, the number of completed projects, and harness size. The number of completed projects is obtained from designers' performance in experimental results.

3.1. Experimental Setup

In this study, an experiment conducted to study the effects of software application in harness design, and development process duration and costs are illustrated. Considering the aforementioned harness development process properties, some evaluation factors are defined and used in this research. These factors are harness complexity, designers' experience, and utilization of software. The first factor is harness complexity that is the size of the harness. Complexity increases as harness size increases and, the number of connectors determines the size of the

harness. 2 connectors-harness refers to small-sized, 5 connectors-harness refers to middle-sized and, 8 connectors-harness refers to big-sized harness. A bigger harness requires more effort and the design period is longer. Designers' experience is the second factor. The experiment measures the performance difference between experienced and beginner designers in terms of design completion time. And the last factor is the utilization of software. Traditional manual harness design and development methods and automated methods with the use of HMS software are compared in this experiment.

Table 3.1 shows the design of the experiment. There are 12 different harnesses in this experiment with three different sizes. Each designer works on each size of harnesses two times. The first work is carried out without HMS, and the second work is realized with an HMS. For example, experienced designer 1 (i=1) works on harness 1 (H1), which has two connectors without HMS, while the second designer works on H4, which also has two connectors and designs without HMS. Then, they exchange their projects, and the first designer works on H4 with HMS while the second designer works on H1 with HMS. Similar exchanges are valid for other harnesses' sizes and designers.

Table 3.1**:** Experimental Matrix

	Harness Size					
	2 Connectors		5 Connectors		8 Connector	
	With HMS	Without HMS	With HMS	Without HMS	With HMS	Without HMS
ED1	H1	H4	H2	H5	H3	H6
ED2	H4	H1	H5	H2	H6	H3
BD1	H7	H10	H8	H11	H9	H9
BD2	H10	H7	H11	H8	H12	H12

Figures 3.1, 3.2, 3.3, and 3.4 show the work of the designers on the projects by the traditional method and HMS method.

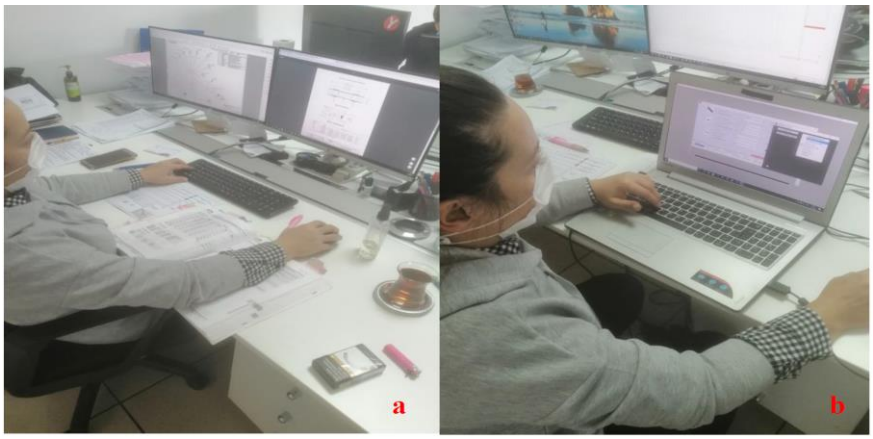


Figure 3.1 Working designer of ED1, a) manual working, b) HMS working

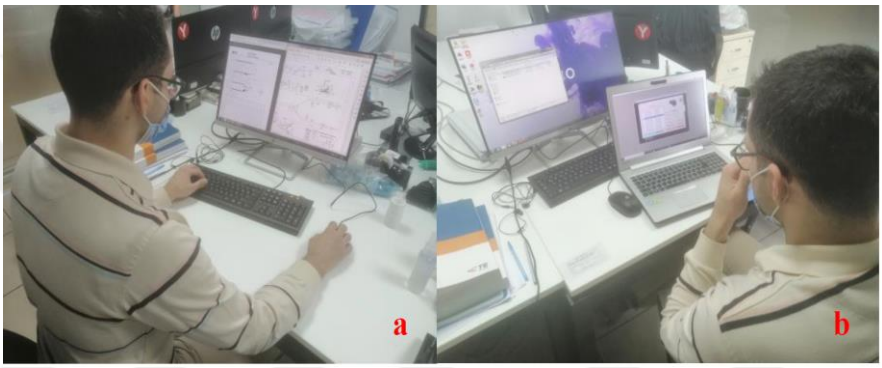


Figure 3.2 Working designer of ED2, a) manual working, b) HMS working

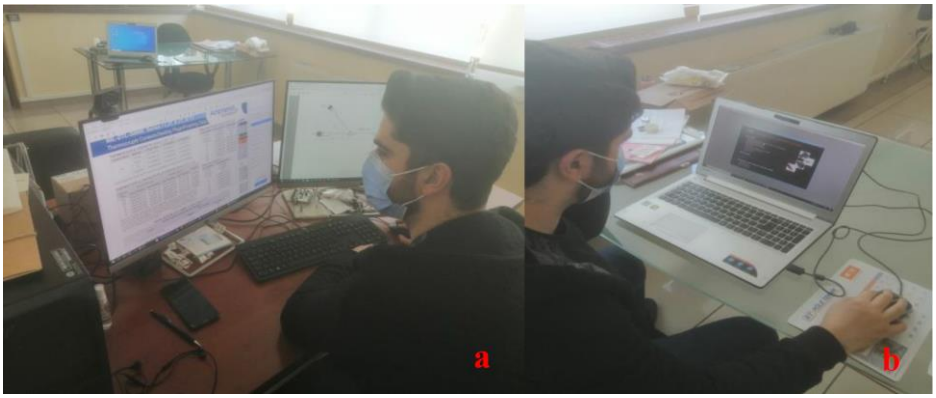


Figure 3.3 Working designer of BD1, a) manual working, b) HMS working

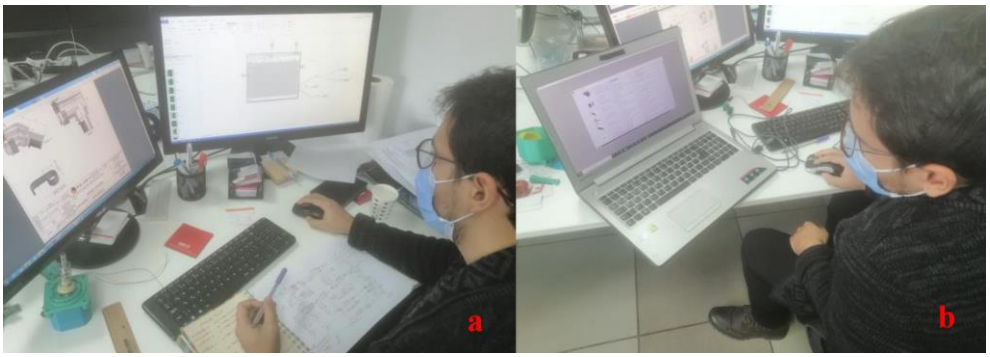


Figure 3.4 Working designer of BD2, a) manual working, b) HMS working

3.2. Cost Model

As mentioned earlier, the harness design process is highly dependent on designer experience. Most of the time during the harness design is spent in selecting appropriate materials and components. Therefore, to decrease the errors due to the dependency of the system on human factors and reduce required design time by bypassing excessive cross-checking multiple datasheets, the harness design software is developed. Graphics and Moore conducted similar research to analyze the cost in the harness production process and optimize wire harness costs concerning their complexity [29]. Their work shows that components' cost decreases and complexity management costs increase as the number of levels increases. The number of levels refers to the different versions of the same harness. For example, assume that two similar cable harnesses are used in automobiles, but one of them has extra fog lamp supporter wires. If one reduces the level of this harness product by eliminating the non-fog lamp option, the harness includes fog lamp supporter wires that have to be ordered for all vehicles even vehicles without fog lamps. Thus unnecessary components cost occurs if the number of levels is decreased. They also considered grouping cost risks and probabilities. In their cost model, cost groups were determined, such as engineering cost, manufacturing cost, testing cost, logistic cost, etc., and risk probabilities were revealed according to historical data. The total risk was accepted higher as the number of levels is increased. The same method is applied in this study to develop the cost model.

Table 3.2. Risk Associated with Different Stages as Presented in [29, Tab. 1]

Band	Cost ($)	Probability (%)	Risk ($)
Engineering	C_{eng}	P_{eng}	$R_{eng} = C_{eng} \times P_{eng} \times N_{levels}$
Validation Testing	C_{val}	P_{val}	$R_{val} = C_{val} \times P_{val} \times N_{levels}$
Manufacturing	C_{mfg}	P_{mfg}	$R_{mfg} = C_{mfg} \times P_{mfg} \times N_{levels}$
Logistics	C_{log}	P_{log}	$R_{log} = C_{log} \times P_{log} \times N_{levels}$
Assembly	C_{assy}	P_{assy}	$R_{assy} = C_{assy} \times P_{assy} \times N_{levels}$
Field	C_{field}	P_{field}	$R_{field} = C_{field} \times P_{field} \times N_{levels}$

3.2.1 Risk Factors and Probabilities

The number of total harnesses designed by a designer in one month is called the "Total Accomplished Project Index" (δ). This index is to evaluate and benchmark the performance of different designers to the most experienced designer. This index facilitates the calculation of risk tolerances according to the percentage of designer salary. Risk tolerances are considered for manual design processes only (without the usage of software). In this way, w_{ij} and v_{ij} indicate the consumed time of each project according to experimental result, type j projects by designer i without and with software, respectively. As it is known, a one-month working period (T) is taken as a hundred; therefore, sample δ index calculations for experienced designers one and two would be;

$$\delta_1 = \frac{T}{(w_{11} + w_{12} + w_{13})} = \frac{100}{10.78} = 9.28 \quad (1)$$

$$\delta_2 = \frac{T}{(w_{21} + w_{22} + w_{23})} = \frac{100}{11.04} = 9.05 \quad (2)$$

Based on these calculations and obtained δ indexes, the first designer ($i = 1$) is 2.5% more experienced than the second designer ($i = 2$); therefore, it can be concluded that the error tolerance rate for the second designer is 2.5% more than the error tolerance rate of the first designer.

$s_i, \mathrm{i} \in \{1,2,3,4\}$ refers to designers' salary

The salary of the most experienced designer is considered as 100 ₺. Salary values, harness size degrees, risk tolerances, and conditions are given in Table 3.3.

Table 3.3. Conditions

Harness Size	Conditions
2	**2C (100%)**, 5C (%0), 8C (0%)
5	2C (0%), **5C (%100)**, 8C (0%)
8	2C (0%), 5C (%0), **8C (100%)**

Table 3.4. Salary and Tolerances

Salary (₺)	Risk Tolerances Based On Performance
s_4 = 75.14	BD2: % 10.92
s_3 = 82.65	BD1: % 10.72
s_2 = 90.91	ED2: % 8.2
s_1 = 100	ED1: %8

Three main risk groups and two design methods in harness design processes are considered in this study. The first risk source is the material selection errors (r_{ms_i}). The second risk source is documentation (r_{d_i}), and finally, the third one is the errors arising from miscalculations (r_{c_i}). Two design methods are the traditional manual harness design method which is realized without benefiting from software (N.H.), and the second method is harness design using design software (H). Subscript i indicates the designer. Based on this notation, the total risks' cost of a harness for each designer can be obtained from:

$$R_i^H = {r_{ms_i}}^H \times {p_{ms_i}}^H + {r_{d_i}}^H \times {p_{d_i}}^H + {r_{c_i}}^H \times {p_{c_i}}^H \text{ , where } i \in \{1,2,3,4\} \quad (3)$$

$$R_i^{NH} = {r_{ms_i}}^{NH} \times {p_{ms_i}}^{NH} + {r_{d_i}}^{NH} \times {p_{d_i}}^{NH} + {r_{c_i}}^{NH} \times {p_{c_i}}^{NH} \text{ , where } i \in \{1,2,3,4\} \quad (4)$$

In equations (3) and (4), R_i^H and R_i^{NH} are total risks' cost for automated and manual harness design methods, respectively. Since harness design duration is highly dependent on the designer experience, the total number of projects a designer may accomplish in a one-month working period would also vary. The other factor which affects the number of total accomplished projects is the usage of the software. In this way, K_{ij} and L_{ij} indicate the number of accomplished type j projects by designer i without and with software, respectively. In these experiments, there are three types of projects. The harnesses with two connectors are the first group of projects ($j = 1$), harnesses with five connectors are considered as the second group ($j = 2$), and harnesses with eight connectors are categorized as thrid group ($j = 3$).

Total risk cost of each project type (y_{ij}^{H} and y_{ij}^{NH}) is depending on the number of projects accomplished per month and the risk cost of each project, therefore:

$$y_{ij}^{H} = R_i^{H} \times L_{ij} \tag{5}$$

$$y_{ij}^{NH} = R_i^{NH} \times K_{ij} \tag{6}$$

Equations 5 and 6 show the total cost of each project type j for automated and manual design processes, respectively. As the number of connectors increases in a harness, its complexity increases, and more time is required to design the harness and there more risks for errors. Since this is the issue, the amount of risk per connector becomes an essential factor in harness design cost analyses; therefore, the number of connectors in a harness determines the amount of complexity and risk in harness design. Let $q_j$be the number of connectors in a harness type j. According to this assumption, $q_1 = 2$ for harness type one, $q_2 = 5$ for harness type two, and finally $q_3 = 8$ for harness type three. Hence, the total designer cost per month is obtained as follows:

$$c_i^{H} = s_i + \sum_{j=1}^{3} \left(y_{ij}^{H} \times q_j\right) \tag{7}$$

$$c_i^{NH} = s_i + \sum_{j=1}^{3} \left(y_{ij}^{NH} \times q_j\right) \tag{8}$$

Equations 7 and 8 give the total cost per month of the designer for manual and automated design methods, respectively. Finally, Equations 9 and 10 reveal the total design cost per project for each designer in manual and automated design processes, respectively:

$$P_i^{H} = \frac{c_i^{H}}{\sum_{j=1}^{3} K_{ij}} \tag{9}$$

$$P_i^{NH} = \frac{c_i^{NH}}{\sum_{j=1}^{3} K_{ij}} \tag{10}$$

CHAPTER 4

RESULTS

In the experiment, designers share their works both manual design and using HMS design. As a result of the experiment, consumed time for each project is determined. Thus, the number of the completed design for a month is calculated. After that, cost results are obtained according to all assumptions, conditions, and experimental outputs.

4.1. Experimental Results

Total working time per month in this study is assumed to be T=100. Designers' performance in designing sample designs is depicted in Figure 7. In order to benchmark designers' performance in a reliable form, designers with similar capabilities and experience levels are given similar projects.

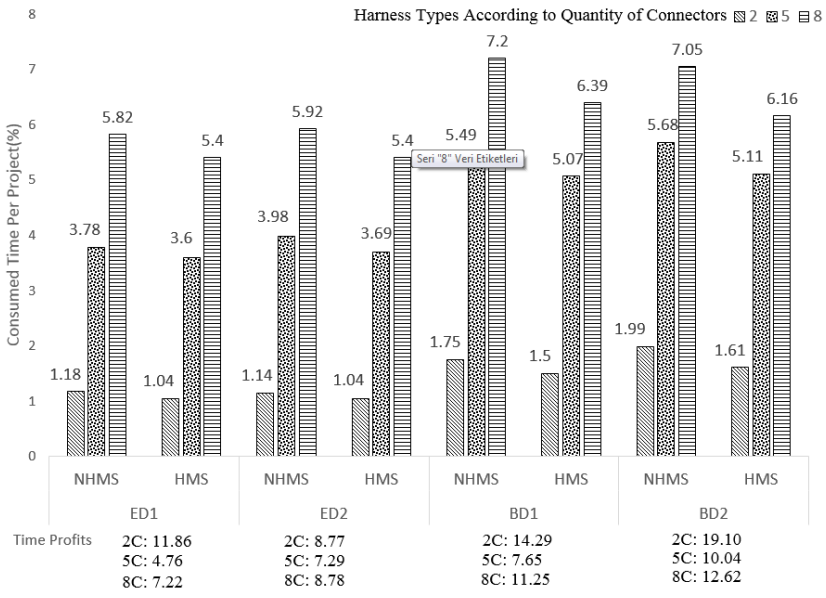


Figure 4.1 Graph of designers' effort in terms of the consumed time

According to Figure 7, all designers reduce the effort time on designs in a month when they use HMS software. Results illustrate that the maximum Reduction in design process duration is realized for the second beginner designer with a rate of 19.10%. In comparison, the minimum effort drop is detected with a rate of 4.76% for the first designer's work on harness with five connectors. The HMS decreases consumed time on designs averagely 13.92% for BD2, 11.06% for BD1, 8.28% for ED2, and 7.95% for ED1. The average design process duration reduction with this software for harnesses with two connectors is 13.51%, for harnesses with five connectors is 7.44%, and 9.97% for harnesses with eight connectors.

4.2. Cost Results

Table 4.1 illustrates the historical risk probability factors of a sample company. These figures are showing the number of mistakes made by a designer. This designer was a beginner-level designer in 2019 and became an experienced one in 2020.

Table 4.1. Mistake Records of Design Projects

	Name Of Projects	Quantity Of Design	Selection Mistakes	Documentation Mistakes	Calculation Mistakes
2019	**Project 1**	46	5	12	5
	Project 2	38	4	8	4
2020	**Project 3**	48	1	7	2
	Project 4	104	1	10	6

The designers' performance index is determined in comparison with the most experienced designer in the enterprise. For instance, in this study, the first designer (experience designer 1 ED1) is assumed as the most experienced designer. ED1 has an 8% error tolerance, and this error tolerance is divided equally into three different risk groups, and each of them would have a 2.67% risk tolerance. According to the comparison between designers (Equations 1 and 2), other designers' error tolerance is assessed. Based on this evaluation, the error tolerance for ED2, BD1, and BD2 would be 8.2%, 10.72%, and 10.92%, respectively. Based on these values, the risk tolerance for each risk group for these designers is 2.73%, 3.57%, and 3.64% for designers two to four, respectively.

Table 4.2. Cost of risk groups per designer

Risk Groups	Risk Cost (₺)			
	ED1 ($i = 1$)	ED2 ($i = 2$)	BD1 ($i = 3$)	BD2 ($i = 4$)
$r_{ms_i}^{NH}$	0.0267	0.0248	0.295	0.274
$r_{d_i}^{NH}$	0.267	0.372	0.59	0.685
$r_{c_i}^{NH}$	0.1335	0.124	0.295	0.274
$r_{ms_i}^{H}$	0	0	0	0
$r_{d_i}^{H}$	0.267	0.372	0.59	0.685
$r_{c_i}^{H}$	0.1335	0.124	0,295	0.274

Table 4.3. Probability of risk groups per designer

Risk Groups	Probability (%)			
	ED1 ($i = 1$)	ED2 ($i = 2$)	BD1 ($i = 3$)	BD2 ($i = 4$)
$p_{ms_i}^{NH}$	1	1	10	10
$p_{d_i}^{NH}$	10	15	20	25
$p_{c_i}^{NH}$	5	5	10	10
$p_{ms_i}^{H}$	0	0	0	0
$p_{d_i}^{H}$	10	15	20	25
$p_{c_i}^{H}$	5	5	10	10

For experienced designer 1 (ED1), the overall risk-related cost calculation is the sum-product of material selection, documentation, and calculation risks' cost values and corresponding probabilities. For instance, the total risk cost for designer one is:

$$R_1^{NH} = r_{ms_1}^{NH} \times p_{ms_1}^{NH} + r_{d_1}^{NH} \times p_{d_1}^{NH} + r_{c_1}^{NH} \times p_{c_1}^{NH}$$

$$R_1^{NH} = 2.67 \times 0.01 + 2.67 \times 0.1 + 2.67 \times 0.05$$

$$R_1^{NH} = 0.4272 ₺$$

In the same manner, the risks' costs can be calculated for other designers :

$R_2^{NH} = 0.5208$ ₺ $R_3^{NH} = 1.18$ ₺ $R_4^{NH} = 1.233$ ₺

$R_1^{H} = 0.401$ ₺ $R_2^{H} = 0.496$ ₺ $R_3^{H} = 0.885$ ₺ $R_4^{H} = 0.959$ ₺

The number of projects designers can design in one month period (δ) in this period can be calculated by the divination of the time value to consumed time per project value from Figure 4.1. The number of completed projects is given in Table 4.4. Some numbers are shown as half because even half accomplished projects are important in terms of saved time, especially for bigger sized- harnesses.

Table 4.4. Number of the Completed Designs

Number of Completed Projects	2C		5C		8C	
	No HMS	HMS	No HMS	HMS	No HMS	HMS
ED1	85	96	26.5	28	17	18.5
ED2	88	96	25	27	17	18.5
BD1	57	66.5	18	20	14	16
BD2	50	62	17.5	19.5	14	16

Since the number of completed projects, the number of connectors, and the total risk cost of error groups are known, the total designers' monthly cost can be calculated using Equations 7 and 8. Table 12 illustrates calculated designers' monthly payments for different harness sizes and design methods.

Table 4.5. Designers Monthly Cost for Different Harness Types and Design Methods

Designer	Total Designer Monthly Cost					
	Non-HMS (Manual Design) c_i^{NH} (₺/month)			HMS (Automated) c_i^H(₺/month)		
	2C	5C	8C	2C	5C	8C
ED1 ($i = 1$)	172.62	156.60	158.10	176.90	156.14	159.35
ED2 ($i = 2$)	182.57	156.01	161.66	182.14	157.87	164.32
BD1 ($i = 3$)	217.17	188.85	214.81	200.36	171.15	195.93
BD2 ($i = 4$)	198.44	183.03	213.24	194.06	168.64	197.89

According to the designers' monthly cost values, the designer's cost per project can be calculated using Equations 9 and 10. Evaluated per project cost of the designers is given in Table 13.

Table 4.6. Cost of Designer per Project for Different Harness Sizes and Design Methods

Designer	Designer Cost per Project					
	Non-HMS (Manual Design) P_i^{NH}(₺/project)			HMS (Automated) P_i^H(₺/project)		
	2C	5C	8C	2C	5C	8C
ED1 ($i = 1$)	2.03	5.91	9.3	1.84	5.58	8.61
ED2 ($i = 2$)	2.08	6.24	9.51	1.94	5.85	8.88
BD1 ($i = 3$)	3.81	10.49	15.34	3.01	8.56	12.25
BD2 ($i = 4$)	3.97	10.46	15.23	3.1	8.65	12.37

Figure 4.2 shows the designers' cost per project in one and half years period. This graph depicts how designers improve themselves over time, and the cost of designers per project reduces during this period.

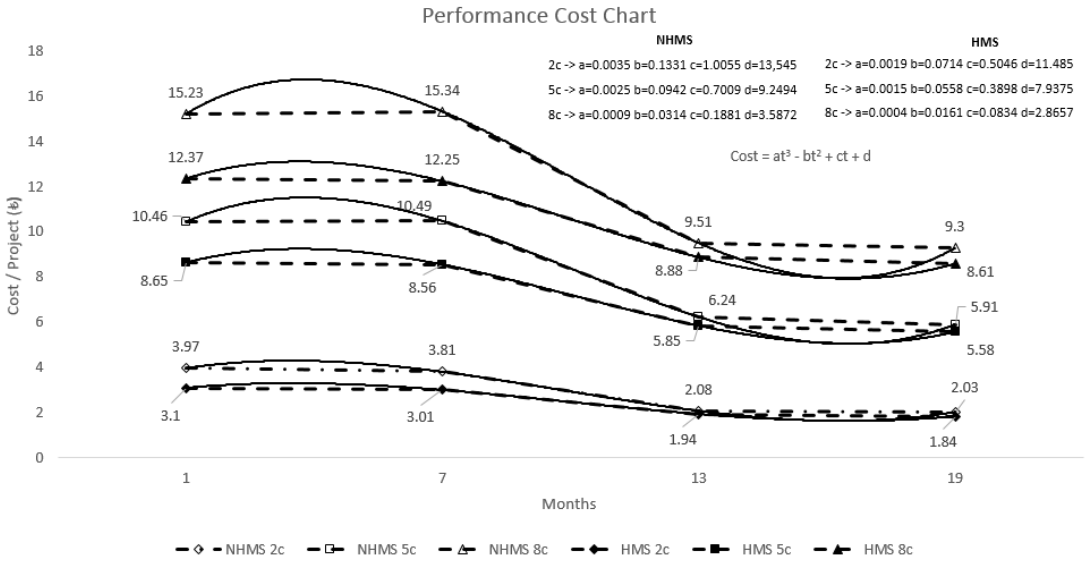


Figure 4.2. Cost-performance chart

Average cost drops for different harnesses types and design methods are shown in Figure 4.3.

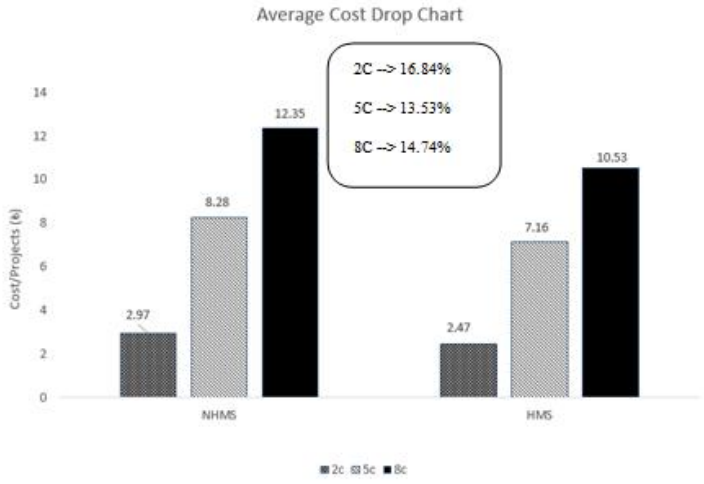


Figure 4.3. Average cost drops per project for each type of harnesses

According to the chart in Figure 4.3, the highest cost drop is shown at 2C type of harnesses as a value of 16,84%, while the lowest cost drop is shown at 5C type of harnesses as a value of 13,53%. 8C type of harnesses has a 14,74% cost drop value.

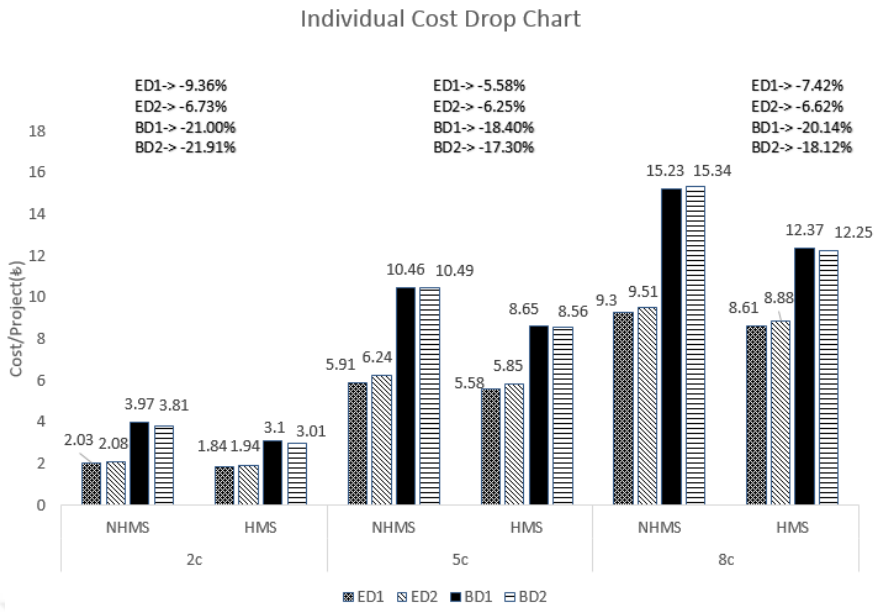


Figure 4.4. Individual cost drop chart

CHAPTER 5

CONCLUSION

Material selection, creation of BOM, skimming through datasheets and standards are challenging and excessively time-consuming activities in harness design and development processes. Meanwhile, this process is highly dependent on the human factor, and the experience and concentration of the designer affect the rate of errors during the design process. Therefore, in this study, to facilitate this process, reduce process period, and minimize human errors, a software tool is developed to automate the harness design process. This paper reveals the outcomes of an experiment and the effects and contributions of developed automation software in harness' design process.

According to depicted Size-Time diagrams, HMS software saved time for all designers. Besides, as expected from the program, it helped beginner designers much effectively and improved their performance considerably. The reason is probably, experienced designers have already known to search needed datasheets, while beginners have put more effort into searching at the first step. Also, this experiment shows the effect of harness size in design durations. Since larger harness size requires more design and processing time, even in the same time-saving rates, the absolute amount of saved time would be higher in large harnesses. However, this is not quite right if the whole one-month performance of designers is considered.

Two design methods named, manual and automated design methods, are applied, and results are compared. The results show that automated design is beneficial for all situations, and all designers fit more projects in a month. Experienced users (ED1 and ED2) accomplish 21.99%, 13.66%, and17.64% more projects containing harnesses with two, five and eight connectors, respectively. while beginner designers (BD1 and BD2) carry out 40.67% 2C, 22.4% 5C, and 28.58% 8C more projects. HMS enhanced the performance of beginner designers more than

experienced designers. This performance improvement directly affects the process cost by reducing the time and rate of errors during the design process. In this study, a cost model consists of effecting factors such as the number of projects, number of connectors for each project, designers' salaries, and designers' experience level is developed. Based on all mentioned factors the cost values per project for one month period are analyzed. When harness size increases, the cost value is also increased for all cases that are expected. Since the HMS software the efficiency of beginner designers more than experienced ones, clearly this method also reduces the beginner designers' costs more than experienced designers. Average cost reduction per project for beginner designers are 21.46% (2C), 17.85% (5C), 19.13% (8C), while average cost drop per projects for experienced designers are 8.05% (2C), 5.92% (5C), 7,02% (8C). According to those results designing harnesses with two connectors seems much efficient economically. The results also depict that in terms of cost reduction per project, harnesses with two connectors 16.84% have the highest reduction rate while, harnesses with eight and five connectors with 14.74%, and 13.53% reduction rates are affected less. In terms of cost of designer per project, the minimum cost achieved for a harness design with two connectors for the most experienced designer (ED1) with a value of 1.84₺. However the highest cost of designer per project using software obtained for beginner designer 2 (BD2) in designing a harness with eight connectors, which both of these results were expected. The average cost reduction ratios are 7.45% for ED1, 6.53% for ED2, 19.85% for BD1 and 19.11% for BD2.

HMS Software improved design process performance in all situations. 2C type straight harness projects have the highest project number and cost drop because designers fit more projects in a month. Since 2C small-type harnesses are simple, completing them is also easy. 2C projects can be worked serially, especially while using HMS. Designers still accomplish more 5C type than 8C type harness projects in one month period, but it isn't enough to pass over 8C type projects' cost reduction. It seems there is a complexity threshold when the size of harnesses size becomes five or bigger. 8C type is bigger and more complex than others. Therefore, since the complexity degree is increased, the cost drop rate is also increased slightly rather than 5C harnesses. In order to find out this complexity level threshold it is extremely required to conduct much higher number of designs with different types of harnesses.

In future works, working with many different harness types is planned to understand the complexity threshold value; therefore, the effects and contributions of HMS or any automation software can be evaluated precisely on time or cost reduction in harness design and development processes. In future work, working with many bigger-sized harnesses and comparing them with each other is planned to understand if there is a specific complexity threshold value. Therefore effect and contribution on cost drop of HMS or any automation software can be measured much better.

REFERENCES

[1] E. Aguirre and B. Raucent, "Economic comparison of wire harness assembly systems," *Journal of Manufacturing Systems*, vol. 13, issue 4, pp. 276-288, 1994.

[2] P. Heisler, D. Utsch, M. Kuhn, and J. Franke, "Optimization of wire harness assembly using human–robot-collaboration," Procedia CIRP, vol. 97, pp. 260-265, 2021.

[3] P. Gao, J. Wen, Y. Hu, "Simulation and optimization of manufacturing process for aircraft harness", *in Proc. ITAIC*, 2014, pp. 550-554.

[4] P. Villanueva-Rey, S. Belob, P. Quinteirob, L. Arrojab, and A. C. Dias, "Wiring in the automobile industry: Life cycle assessment of an innovative cable solution," *Journal of Cleaner Production*, vol. 204, pp 237-246, Sep. 2021.

[5] F. Del Pero, M. Delogu, and M. Pierini, "The effect of light weighting in automotive LCA perspective: Estimation of mass-induced fuel consumption reduction for gasoline turbosignald vehicles," *Journal of Cleaner Production*, vol. 154, June 2017.

[6] Zhou, Jia Fu, and Jie Sheng Wu. "The Simulation and Fatigue Life Prediction of a Cable Harness in an Industrial Robot." *Key Engineering Materials*, vol. 464, Trans Tech Publications, Ltd., Jan. 2011, pp. 293–298.

[7] D. G. Ocaktan and H. A. Ulusu, "Analysis of working postures in a wiring harness conveyor line with AnyBody Modeling System and design proposal of a new line," *Journal of the Faculty of Engineering and Architecture of Gazi University*, vol. 36, no. 3, pp. 1303-1317, Jan. 2021

[8] J. M. Bernardes, C. Wanderck, and A. Moro, "Participatory ergonomic intervention for prevention of low back pain: assembly line redesign case," *Work-A Journal of Prevention Assessment & Rehabilitation*, vol. 41, no. Supplement 1, pp. 5993-5998, 2012.

[9] E. K. Delice, G. F. Can, and E. Kahya, "Improving the rapid office strain assessment method with an integrated multi-criteria decision making approach," *Journal of the Faculty of Engineering and Architecture of Gazi University*, vol. 35, no. 3, pp 1294-1314, Jan. 2020.

[10] Ramsey T., Davis K., Kotowski S., Anderson V., and Waters T., "Reduction of spinal loads through adjustable interventions at the origin and destination of palletizing tasks," *Human Factors*, vol. 56, no. 7, 1222-1234, Nov. 2014.

[11] V. Castorani, P. Cicconi, M. Mandolini, A. Vita and M. Germani, “A method for the cost optimization of industrial electrical routings,” *Computer-Aided Design and Applications*, vol.15, no. 5, pp. 747-756, 2018.

[12] C. W. Lin and A. Sangiovanni-Vincentelli, L. Rao and J. D’Ambrosio, “Electrical Architecture Optimization and Selection-Cost Minimization via Wire Routing and Wire Sizing,”, *International Journal of Passenger Cars – Electronic and Electrical Systems*, vol. 7, no. 2, pp. 502-509, Aug. 2014.

[13] W. P. J. Pemarathne, and T. G. I. Fernando, “Wire and cable routings and harness designing systems with AI, a Review,” *in Proc. ICIAfS*, pp. 2016, 1-6.

[14] J. M. Ritchie, G. Robinson, P. N. Day, R. G. Dewar, R. C. W. Sung, and J. E. L. Simmons “Cable harness design, assembly and installation planning using immersive virtual reality,” *Virtual Reality*, vol. 11, issue 4, pp. 261-273, Oct. 2007.

[15] M. Pitt, S. Goyal, P. Holt, J. Ritchie, P. Day, J. Simmons, G. Robinson and G. Russell “An innovative approach to facilities management in the workplace design brief,” *Facilities*, vol. 23, no. 7/8, Feb. 2005.

[16] F. Yumbla, J. S. Yi, M. Abayebas, M. Shafiyev, and H. Moon, “Tolerance dataset: mating process of plug-in cable connectors for wire harness assembly tasks,” *Intelligent Service Robotics*, vol. 13, pp. 159-168, Dec. 2019.

[17] K. Duan, F. Zhu, Y. Li, K. Tang, and Sheng. Liu,. “Contact Resistance Investigation of Electrical Connector with Different Shrink Range,” *in Proc. ICEPT*, 2014, pp. 1146-1149.

[18] L. O. Hoeft, and J. S. Hostra “Measured Electromagnetic Shielding Performance of Commonly Used Cables and Connectors,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 30, issue 3, pp. 260-275, Aug. 1988.

[19] J. Verpoorte, H. Schippers and J. H. G. J. Lansink Rotgerink “Advanced models for the transfer impedance of metal braids in cable harnesses,” *in Proc. EMC*, 2018, pp. 187-192.

[20] S. W. Glass, L.S. Fifield, A. Sriraman, W. C. Palmer, and N. Bowler, “Inter-digital capacitive sensor for evaluating cable jacket and insulation aging”, *in Proc. AIP*, 2019, pp. 020024-1–020024-9.

[21] R. Kraus and D. Ryan, “Advances in Heat-Shrink Technology,” *IEEE Electrical Insulation Magazine*, vol. 4, issue 3, June 1988.

[22] J. P. Mackevich and J. W. Hoffman, “Insulation Enhancement with Heat-Shrinkable Components Part 111: Shielded Power Cable”, *IEEE Electrical Insulation Magazine*, vol. 7, issue 4, Aug. 1991.

[23] M. Runde, R. S. Timsit and N. Magnusson1, “Laboratory performance tests on aluminum splices for power conductors,” *European Transactions on Electrical Power*, vol. 20, no. 4, pp. 450-460, 2010.

[24] C. DANG and M. BRAUNOVI, “Metallurgic and contact resistance studies of sleeve connectors in aluminum cable splices,” *in Proc. IEEE Holm Conference on Electrical Contacts*, 1989, pp. 229-236.

[25] N. S. Ong, “Activity-based cost tables to support wire harness design,” *International Journal of Production Economics*, vol. 29, no. 3, pp. 271-289, Jan. 1993.

[26] Shi Yu-qiang, W. Jun Jia, “Optimization of Production System by Simulation Based on UML and Flexsim,” *in Proc. MASS, 2011*, pp. 1-4.

[27] C. Larman, “Activity Diagrams” in Applying UML and Patterns, 2nd ed., 1997, pp. 607-608,

[28] TE Connectivity, “HarnWare Software”, Internet:

https://www.israyfast.com/media/pdfs/lib/TE%20Literature/HarnWare.pdf, [Jan

2014].

[29] S. Moore, “Modeling and optimizing wire harness costs for variation complexity,” *in Proc. SAE*, 2016, pp. 1-9.

APPENDIX A

HMS INTERFACE GUIDE

This guidance helps the designer how to choose corresponding and alternative materials and creating BOM during the material selection process. Also, it shows how to quickly drawing, storing information, and update steps by step.

- HMS entry interface:

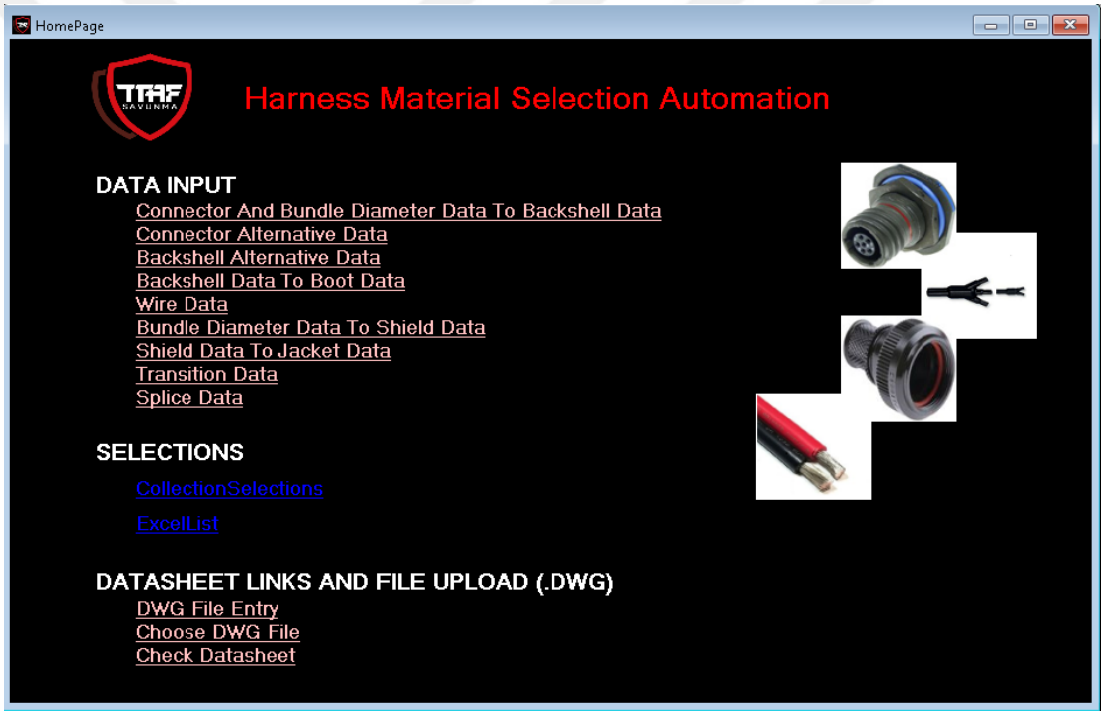


Figure A.1 HMS opening screen

Titles:

a. Designers can enter new data, remove wrong or unnecessary data or do some arrangements and updates on specific data in this section. This section is like information storage and can be used as the database of section b.

b. This is the automation section. Designers can select needed materials automatically and create the material list. This section is fed from section a.

c. In this section, a connector, backshell, and boot assembly or a transition and splice detail drawing is stored in AUTOCAD format and it can be selected from s simple code. When the designer enters a code of material, the 2D drawing of this material is also integrated into the code. After integration, at any time, the designer can search and select a code, then the material's drawing comes automatically. Also, a material datasheet extension can be added to this section.

- Connector-backshell data:

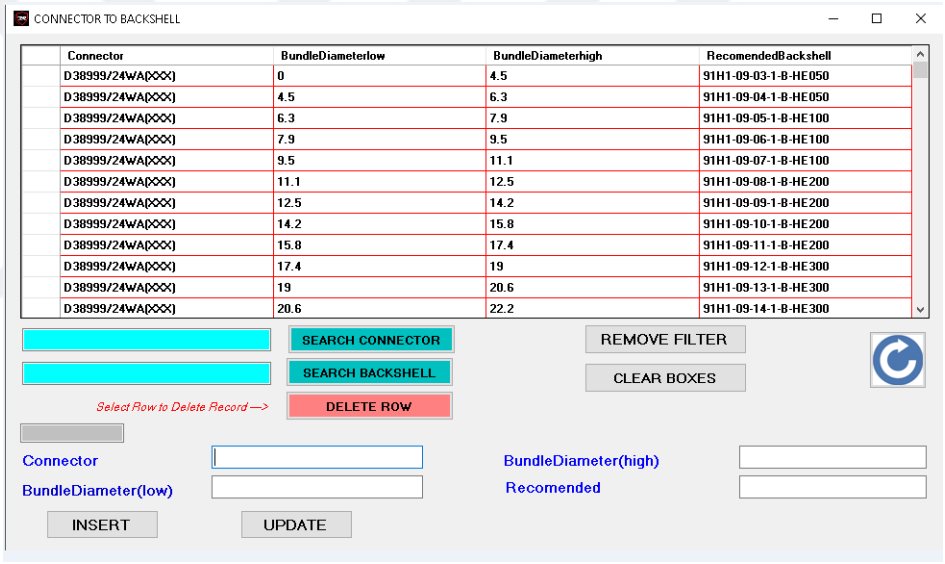


Figure A.2 Connector-backshell arrangement screen

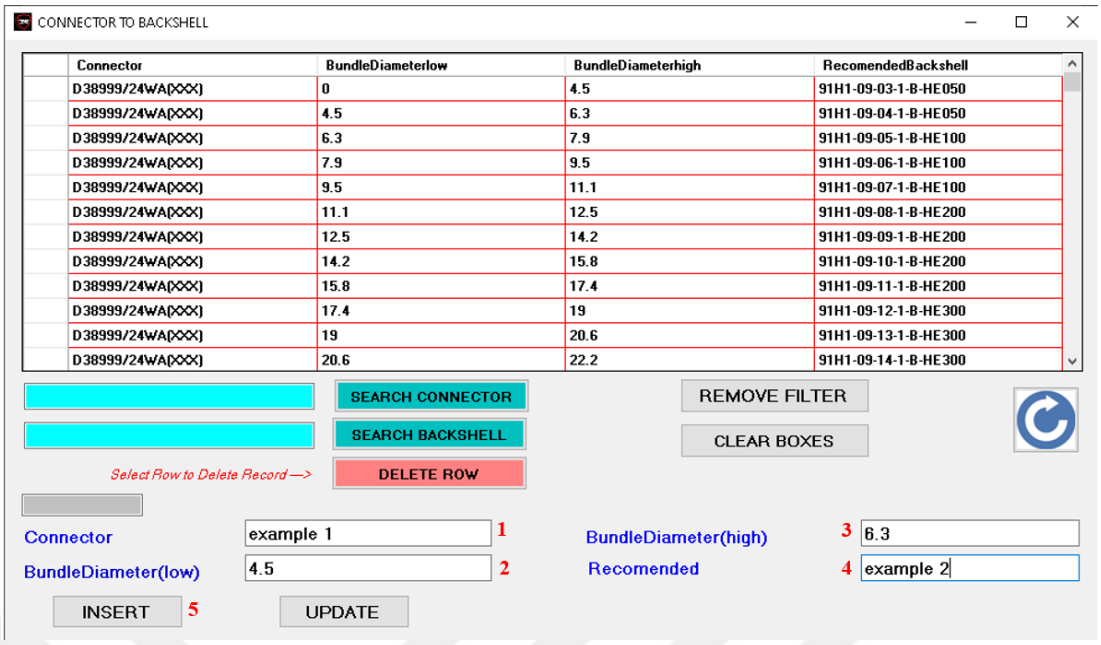


Figure A.3 Data entry for connector-backshell

Steps from Figure A.3.:

1. Enter connector code.
2. Enter minimum bundle diameter value.
3. Enter maximum bundle diameter value.
4. Enter backshell code
5. Click “INSERT”.

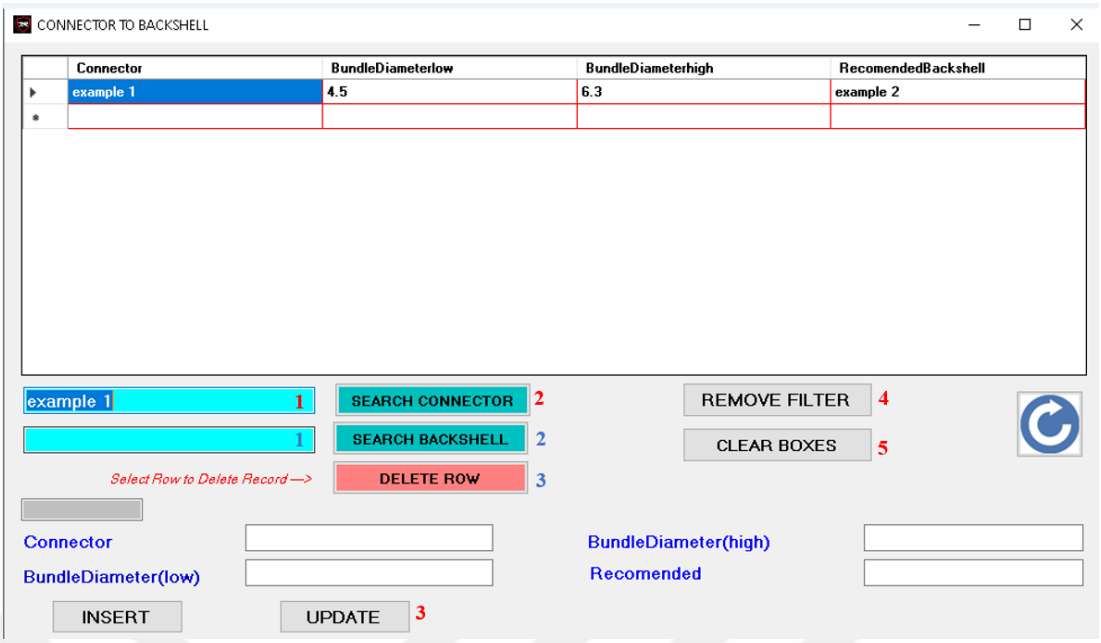


Figure A.4 Code searching and removing

Steps from Figure A.4:

1. Enter connector or backshell code to the blue area.
2. Click search connector or click search backshell.
3. If any arrangement is needed, click the "UPDATE" button or if any unnecessary information exists, click "DELETE ROW".
4. Clicking "REMOVE FILTER" cancels searched information and brings all previous information back.
5. Clicking "CLEAR BOXES" cancels all written information into empty boxes.

Note: This logic is similar to other processes' steps. Red numbers express main, blue numbers express alternative steps.

- Connector-alternative data:

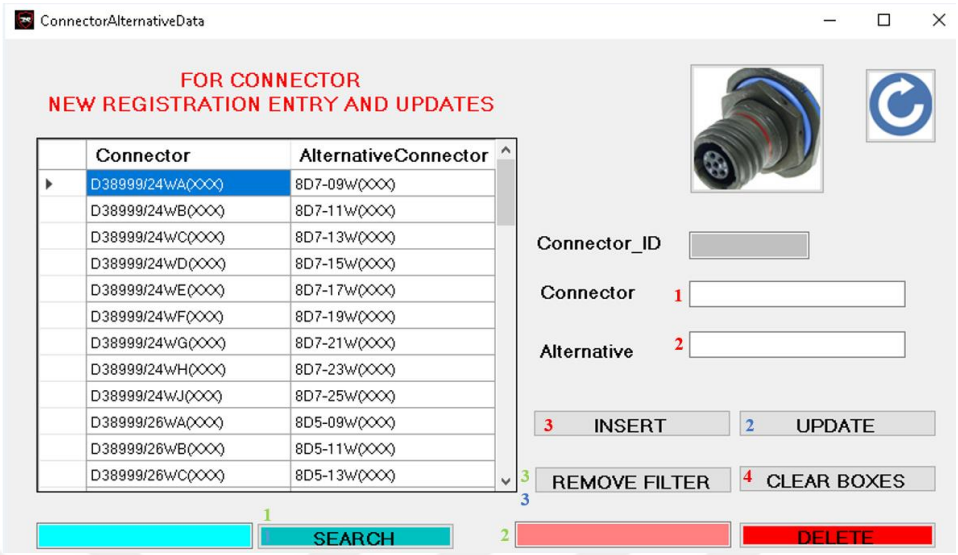


Figure A.5. Connector-alternative data arrangement screen

Red numbers are main, blue and green numbers are alternative steps for all processes.

- Backshell-alternative data:

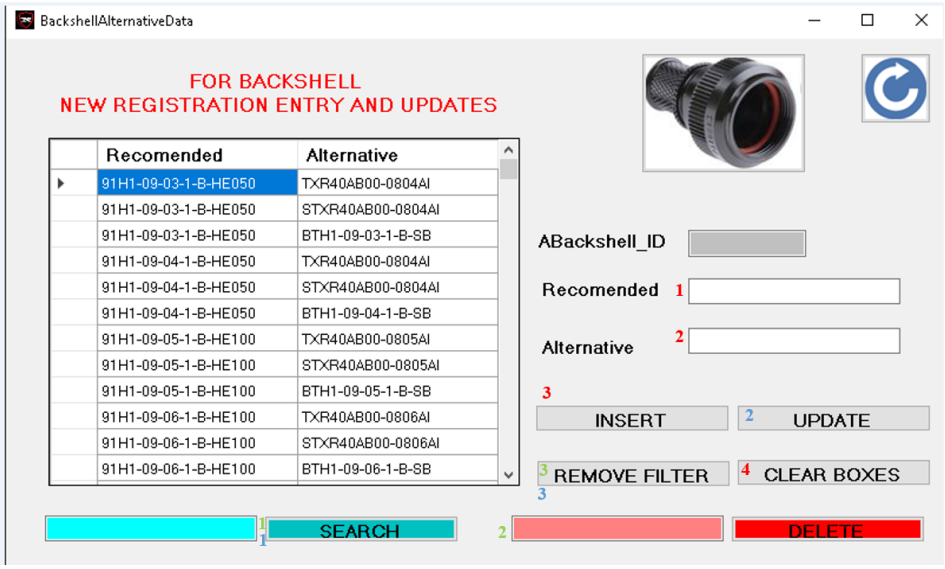


Figure A.6. Backshell-alternative data arrangement screen

- Wire-alternative data:

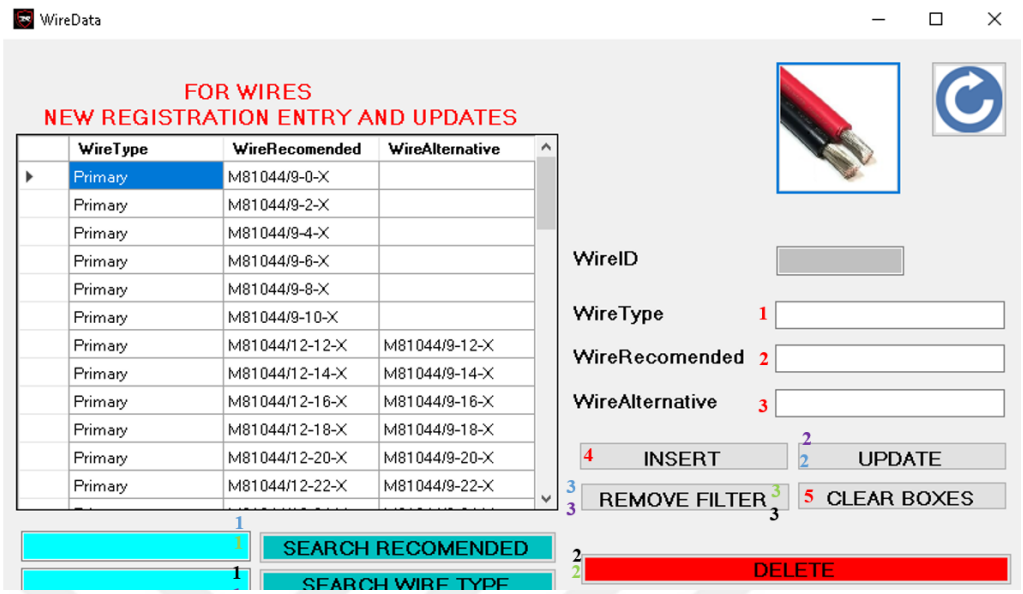


Figure A.7: Wire-alternative data arrangement screen

Red numbers are main, blue, green, black, and purple numbers are alternative steps for all processes.

- Bundle diameter-shield data:

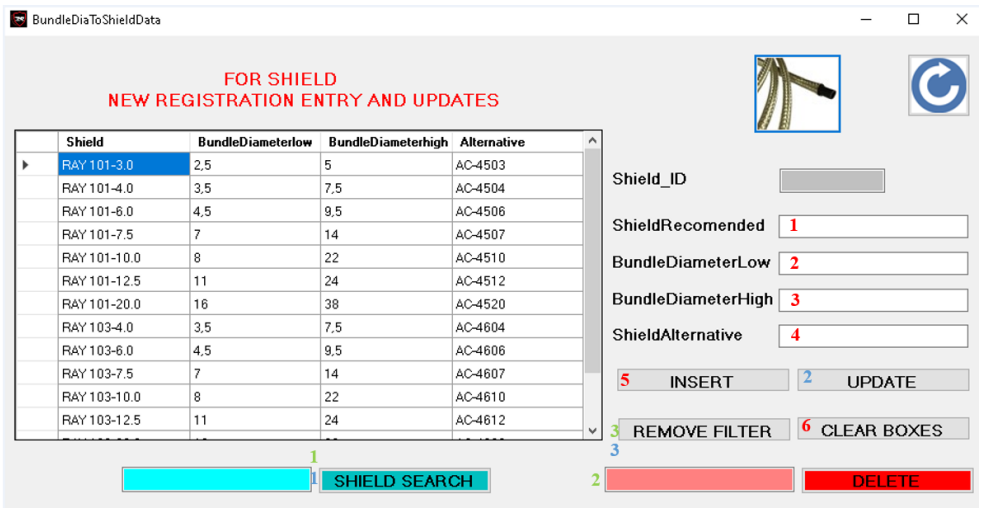


Figure A.8. Bundle diameter-shield data arrangement screen

- Shield-jacket data:

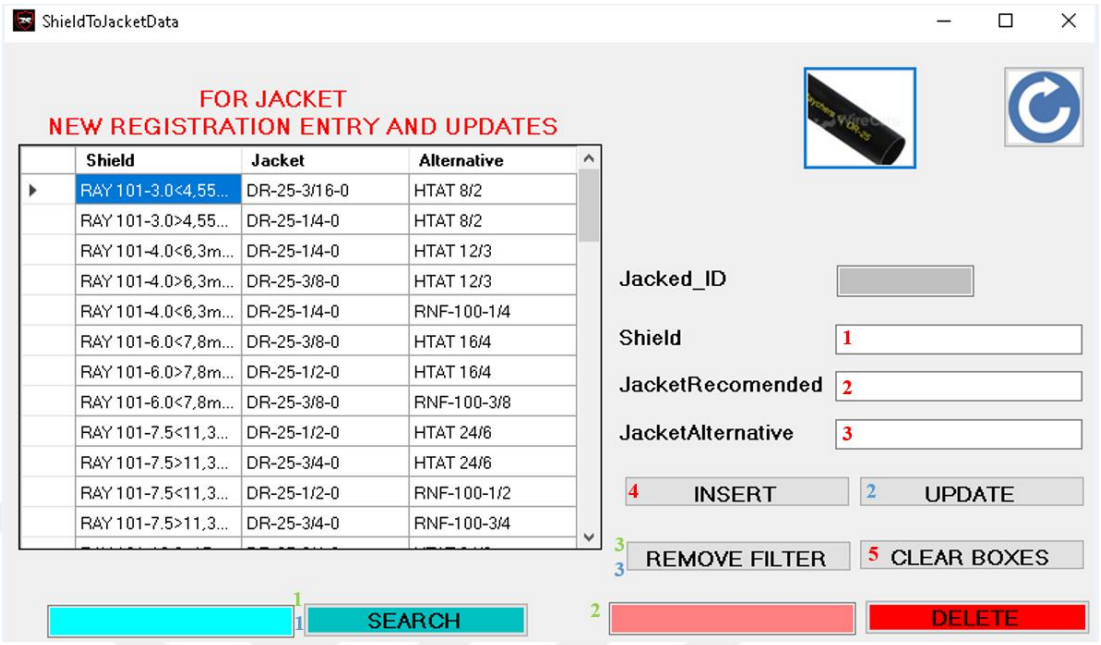


Figure A.9. Shield-jacket data arrangement screen

- Transition Data

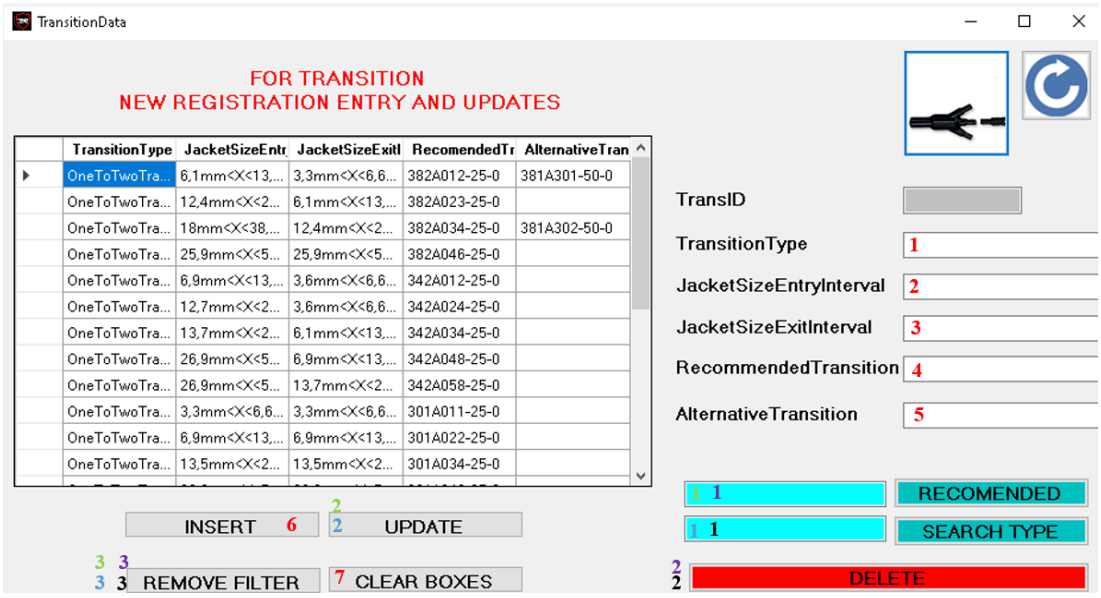


Figure A.10. Transition data arrangement screen

- Splice Data:

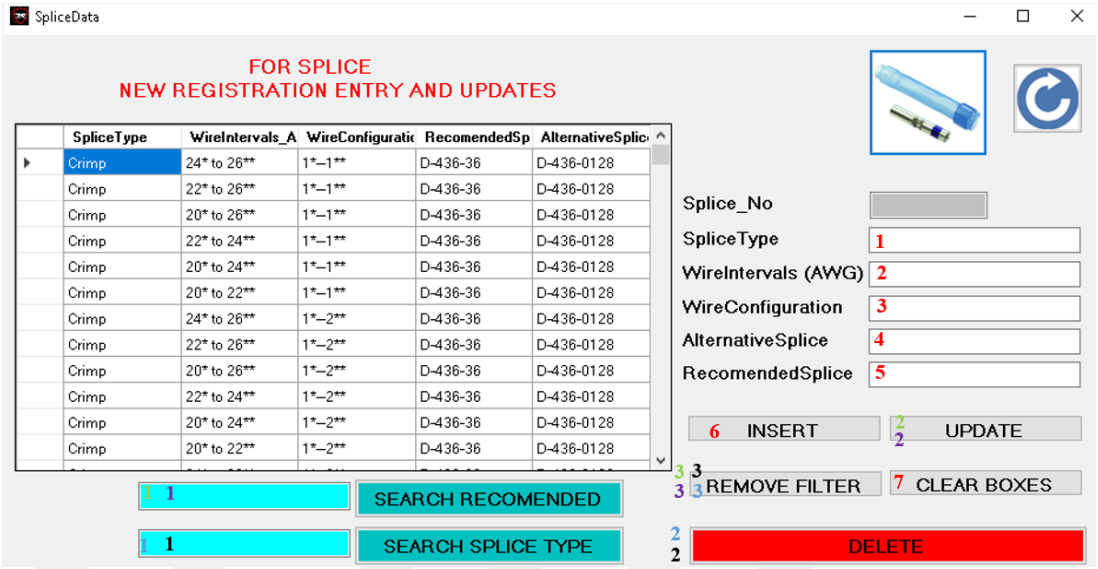


Figure A.11. Splice data arrangement screen

- Material selection:

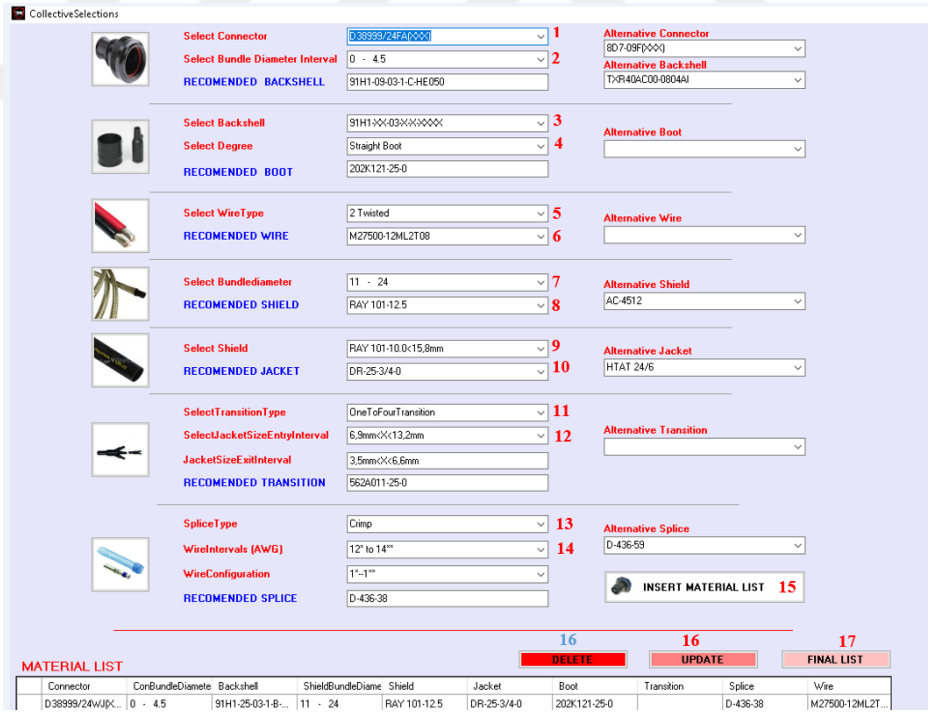


Figure A.12. Material selection screen

Material Selection Steps:

1. Enter connector code from the data package.

2. Enter bundle diameter interval.

   Backshell is automatically selected by software.

3. Enter selected backshell code.
4. Specify the type of boot.

   The boot is automatically selected by the software.

5. Specify the type of wire.
6. Enter code of wire from data package.
7. Enter bundle diameter interval calculated from Harnware or excel formula or manually calculation methods.

   The shield is automatically selected by software.

8. Add 0.8mm to bundle diameter, and enter the code of the selected backshell. There are some options in this step. According to the overall shield diameter on the bundle, select the suitable value of the determined shield which diameter value is smaller or bigger than a specific value. (This part can be selected by Harnware)

   The jacket is automatically selected by software.

9. Specify the type of transition if there is a need.
10. Add the thickness of the selected jacket which is given from Figure 36 on overall shield diameter or add as the average of 1.5mm on overall shield diameter.
11. Specify outer diameter interval between specific values for transition's entry and exits.

    Transition is automatically selected by software.

12. Specify the need for a splice or solder sleeve.
13. Enter AWG values.
14. Enter wire configuration.

    Splice is automatically selected by software.

HMS may suggest some alternative materials. The designer can select those materials too if the main materials are hard to obtain.

15. Click the "INSERT MATERIAL LIST" button to add a row to the material list table.

Those steps can be repeated for each branch of the harness.

16. Designers can delete an unnecessary row by clicking the “DELETE” button or can click the “UPDATE” button after inserting material or manually change something in the material list.

    For example, a row is completed and inserted into the material list but there is no need to splice according to the data package. Therefore, users can delete unnecessary materials from the material list manually then click the “UPDATE” button.

17. After all, arrangements are completed, click the “FINAL LIST” button.

- BOM:

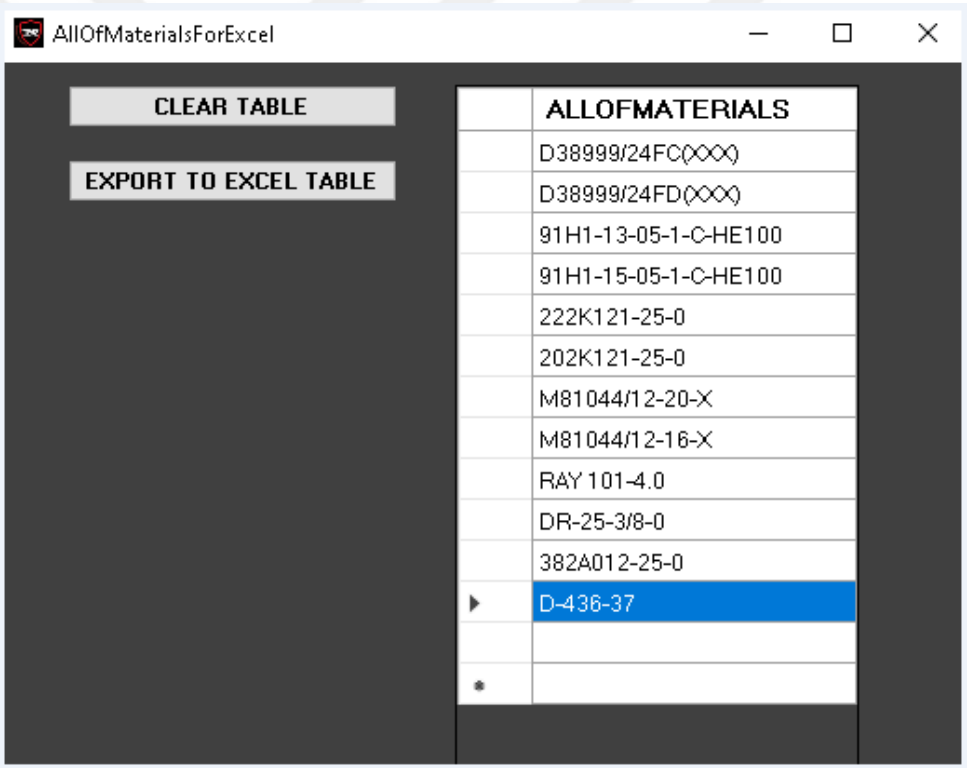


Figure A.13. BOM screen

After the final listing, a BOM screen will appear. If designers are sure about materials, they can import BOM to excel.

Designers should click the “CLEAR” button on the BOM screen before they start the new harness design if they don’t list, new selected materials are added to the old list.

- Code-DWG:

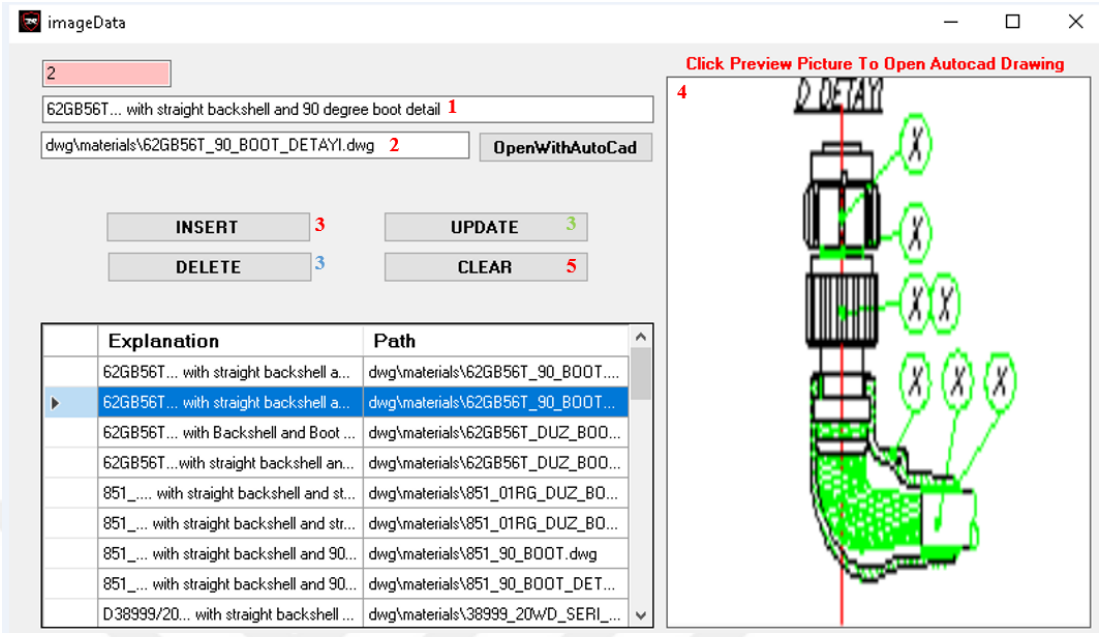


Figure A.14. Code to AUTOCAD screen

Steps:

1. Enter code and description of materials.
2. Add extension of drawing in AUTOCAD Format.
3. Click “INSERT” or if any row should change, click “UPDATE” or click “DELETE”
4. Click the preview picture to open 2D AUTOCAD Drawing.
5. Click “CLEAR” after the finish.

- Code-datasheet:

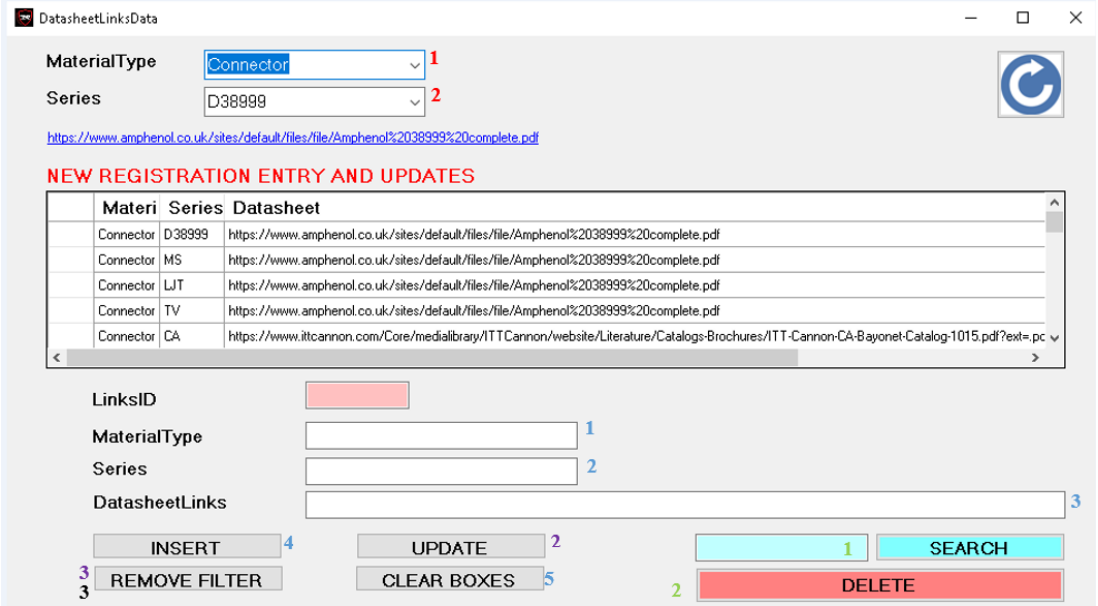


Figure A.15. Code to datasheet screen

Steps of selection:

1. Specify the type of material.
2. Specify series of materials.

Steps of Data Arrangement

1. Write material type or search a specific material name.
2. Write material series if new data is needed to be entered. If there are any data searches, the designer can click “UPDATE” in case of arrangement on a specific searched row or can click “DELETE” to remove a specific data from searched row.
3. Found data sheet link from ınternet is pasted on the area of “DatasheetLinks”. Another case is if a search is updated or completed, the designer can click “REMOVE FILTER” to bring all data.
4. If new materials, series, and links are written from steps 1, 2, 3, click the “INSERT” button to store that information in the software system.
5. After new data is entered, designers can click the “CLEAR BOXES” button.