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Procedia CIRP 34 (2015) 180 – 185

www.elsevier.com/locate/procedia

9th International Conference on Axiomatic Design – ICAD 2015

Investigation on optimal mobility system using Axiomatic Design and Scoring Matrix: the "Drive Ability" experiment

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Abstract

The increase in the global population and the improvement of the life style of many poorer countries are leading to a relevant growth for mobility. Such increase in circulating vehicles would have a negative impact on environment pollution. Given this picture, the traditional internal combustion engine vehicles could not be the best solution for the future personal mobility. This problem is really critical especially for high population density cities, such as Firenze (Italy), where the large number of circulating vehicles must use a very old infrastructure that is constrained by all the historical sites widespread in the city, that are also very sensitive to air pollution. However, choosing between the possible mobility solutions could not be an easy task, also if using a structured approach. The challenge is, in fact, to assess a large number of variables for different solutions, process that could lead to a situation where all scenarios show pros and cons, and so all matrices will be decoupled and will not be possible to define which solution is the best. The aim of this paper is to define a new approach, based on a Scoring Matrix and on the Axiomatic Design, which overcomes this issue by using a multi-criteria evaluating strategy. This new approach has been tested on the city of Firenze (Italy) where the optimal mobility paradigm has been assessed from the sustainability point of view. As a result, the wireless charging system has been identified as the most suitable for the city and citizen needs. In addition, Axiomatic Design has been used to define how to overcame the technological barriers for its introduction: wireless charging introduction, in fact, could experience a stop due to the efficiency loss in case of misalignment. In this paper, the scenarios are introduced using the Axiomatic Design decomposition tree and the solution has been tested by using the information axiom.

Peer-review under responsibility of the organizing committee of 9th International Conference on Axiomatic Design

Keywords: Mobility needs assessment; Electrical vehicles; Scoring Matrix; Driving attitude; Wireless city

Introduction

In the last years the relevance of environmental impact of vehicles has experience a strong increase due to the approval of the new directives of the Kyoto protocol, the tests that prove effects on human health [1] and the more than ever evident corrosive effect on monuments and historical masterpieces [2]. This problem affects greatly the larger Italian cities: in fact, their historical centers often suffer for the centuries old road infrastructure that is usually responsible for traffic congestions and local pollution increase. One important example is the city of Firenze [4], where 5 km^2 of the city center has been declared UNESCO site and hosts a large number of historical buildings together with an high population density. Moreover the high concentration of tourists led to the need of mobility specifically in these historical areas, where the economy growth [5] is strongly related to the touristic presence. Another incentive purse a shift to an electrical based mobility is the ever increasing cost of fossil fuel: in the last years, gasoline and diesel have suffered a strong increase in their costs and alternative fuels can't completely replace traditional ones at the actual state of technology [6]. Nowadays the available electrical mobility solutions have still some open issues that limit their mass introduction in the market. Probably the most limiting constraint is the battery autonomy and very high replacement costs, but also the lithium production can be an interesting challenge to be addressed [7]. For this reason, research is going to develop more performing solutions and strategies to overcome these limitations. To design a new mobility paradigm, however, is not an easy task; in fact, structured approaches are very useful when the parameters to be assessed are few. The aim of this paper is to introduce a new approach able to manage a large number of choosing

Peer-review under responsibility of the organizing committee of 9th International Conference on Axiomatic Design
doi:10.1016/j.procir.2015.07.066

parameters: the Scoring Matrix will investigate the most suitable mobility paradigm (screening approach) and then the Axiomatic Design will be used to go into design details.

1. Sustainability concept

A large number of studies have been performed to determine the optimal battery weight/volume for Pure Electric Vehicles (PEV), but they generally agree on the issue that the number of kilometers daily travelled are less than the capacity industrial battery equipped on PEVs [8]. In general, replacing the internal combustion engine with an electric one is the easier way to introduce electric vehicles in "all day life" and also the most similar to the traditional mobility model. Vehicle (electric/ICE vehicle) has a "tank" (the battery/the fuel tank) that is equipped on the vehicle and a fixed infrastructure (recharge columns/fuel stations) territorially distributed. However, at the actual state of the art, the speed to recharge the battery can't be compared with the speed to "recharge" the traditional fuel tanks and, most important, vehicles' battery energy density is extremely lower than fossil fuels one. These two limitations are strictly related to the sustainability of mobility. The definition of sustainability adopted in this paper includes both the environmental issues related to the vehicle pollution but also to the user acceptance; in general, a vehicle is not sustainable for an end-user if this introduce relevant limitations to his mobility or difficulties in its utilization [9]. In order to evaluate the best sustainable solutions among the available technologies, a Scoring Matrix that includes a larger concept for sustainability and provide a more objective analysis of the effectiveness of the studied solutions has been developed. The EV compared technologies are:

- Electric Vehicle with Internal Combustion Engine Range Extender.
- Electric Vehicle with Fuel Cell.
- Rapid Battery Change Station + Private Recharge with Columns.
- En Route Recharge System.

2. The Scoring Matrix

The data used to fill the matrix comes from literature [10] and from end users surveys.

The Scoring Matrix is a graphical representation of data where on the Y axis are reported "Choosing Parameters", "Direction of Improvement" and "Weighting system", on the X axis is reported the list of technologies to be evaluated as it is described in Figure 2 – *Part a* and *Part b*.. More in details:

- Technologies: the solutions to be evaluated.
- Choosing Parameters: the fundamental aspects to evaluate the performances of the different solutions. Later in this paper, developed parameters will be presented extensively. This model, however, also allows to add other if deemed important for the designer.
- Direction of Improvement: identifies if each parameter has a positive impact on the result if increasing (↑) or decrease sing (↓). i.e.: CO2 emission has a degradation effect on the environmental impact of mobility.
- Weighting System: weight for each parameter; it is a number between "0" and "1" and it is used to multiply the value of each parameter before calculating the final result. For the developed test, results of a survey on Firenze's inhabitants expressly built for the case study has been used.
- Values: performance values for each parameter and for each technology.

Once the matrix is filled, results are calculated. The results come from the following expression, for each column:

$$Score\ Technology\ j = \sum_{i=1}^{n} Parameter_i * Weight_i \quad (1)$$

with n=Number of Parameters.

The best technology will be the one with the highest value.

In addition, a diagram to relate the interactions between the parameters has been developed in order to understand the effect of parameters interaction. The relation diagram will be presented later on the paper.

3. The Parameters Tree

In this section the tree of parameters chosen to evaluate the different technologies are presented. To be sure that the parameters will cover all the important issues of the problem, a structured approach to find them has been used: the idea is to divide the macro-problem in sub-problems with increased level of details, according to the Axiomatic Design framework. It is important to notice that his is not a direct Axiomatic Design application, it is a preliminary study to identify the most promising solution to be deeply analyzed with the classic AD strategy and so it is not mandatory to use the zig-zag method. So, firstly two macro-areas have been defined dividing the parameters between "technical" and the ones that are relevant for customer satisfaction (they will be called from here "Technical" and "Customer"):

The technical ones will be strictly related to feasibility and costs and the customer ones will be the key factors to fast-forward the introduction of a new technology paradigm.

Afterwards, these two macro-categories have been divided in six more subsets; three more subsets for Technical parameters and three for Customer parameters. Technical parameters have been divided in "Feasibility", "Upgradeability" and "Environment", where the Customer parameters have been divided in "Satisfaction", "Delighters and "City Planning". More in details:

- Feasibility: numeric parameters related to the solution feasibility under the actual technological constraints.
- Upgradeability: Solution flexibility due to the technological continuous development. All the technologies are at early lifecycle stage, it is important understand the upgradeability (e.g. nanoscale supercapacitors with vs battery [15]).
- Environment: Environmental impact during all the product life cycle.
- Satisfaction: Key features needed by the customer; if this kind of properties are not guaranteed, the customer will never change his habits.

- Delighters: this kind of parameters are non-core requirements and the end user does not ask for them directly, but they can delight the customer and make him decide for alternative mobility solution because of its benefits. It is important to notice that to switch to the new technology paradigm should be easier if these parameters are as high as possible. However, they are the most difficult to evaluate because is not possible to quantitatively determine them [16].
- City Planning: this parameter evaluates the aesthetic and user needs impact of the technology on the whole city, e.g. pantograph and overhead cable could be a problem for aesthetic and rails could be a problem for wheel chairs.

4. The Choosing parameters

Once defined the parameters tree, next step is to fill them with indicators to numerically express their different characteristics. in the left part of Figure 2 – *Part a*, it is reported the parameters together with the related measurement unit (if available). In that table is possible to divide the parameters in two groups according to the "Countable" record:

- Countable Parameters: possible to extrapolate the data needed from literature, technical sheets, cost analysis, etc. It will be a numerical index. Starting from this data, it will be assigned a value from 1 to 5, where 1 is a bad result according to others and 5 is a good result according to others.
- Uncountable Parameters: the values must be assigned thanks to an assessment of customer opinions. In order to have a more objective and reliable assessment a table to define the scoring rules for each uncountable parameter has been developed. An example for a choosing parameter in Table 1:

Table 1. Example for uncountable parameter scoring table.

Hazardness of the Solution		
Effect	**Description**	**Value**
Critical without Warning	Direct risk for users life and third parties without any warning before the faliure	1
Critical with Warning	Direct risk for users and third parties life, but with warnings before the faliure	2
Very High	Impairment of the vehicle with risk for the life or safety of the user and third parties	3
Moderate with Warning	Impairment of the vehicle with risk for the safety of the user and third parties, but with large time to abandon the vehicle	4
Absent or very Negligible	No direct risk for life and safety of users and for third parties	5

A cross correlation matrix to assess how the parameters can influence each other if a change occurs has been also developed. In Figure 1 are reported the parameters mutual influences:

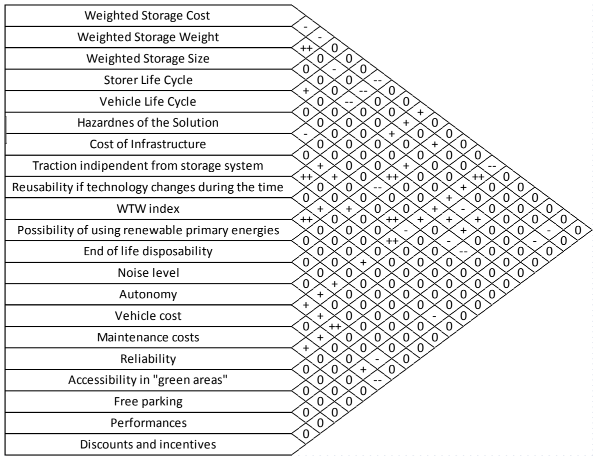

Fig. 1 - Correlation between parameters

- "+ +": The two parameters have a strong positive correlation
- "+": The two parameters have a positive correlation.
- "0": The two parameters are indifferent. A variation of the first does not influence the second.
- "-": The two parameters have a negative correlation.
- "- -": The two parameters have a strong negative correlation

From this matrix:

- Some parameters affect a large number of other parameters. It becomes very important to assess them as precisely as possible, to reduce the probability of systematic errors.
- The delighters are quite indifferent to other parameters. To increase them the only strategy is to invest resources directly on them.

5. The mobility survey

A survey has been performed to characterize the needs for electric mobility in Firenze. The statistical sample of people has not been chosen randomly: in fact, the needs were to interview a set of people technically prepared. The questionnaire was send to 80 persons and 53 answers (66.25%) have been obtained. Most of the answers come from the academic world, both professors and post-degree student of industrial engineering (83%), while the rest (17%) come from automotive industries experts. The idea has been to focus the interviews on experts to be more in touch with the technologies state of the art and to exclude personal feelings of end users. The main objective of the survey are:

- Identify the relative importance of the parameters (assign the weights).
- Understand the perceptions about performance of the four technologies to be evaluated.

All the question are closed ones, so it is possible to give only an answer that can be transformed in a numeric index, from 1 (very low importance) to 7 (very high importance). Also a 0 value is possible if not applicable.

The results have been analyzed also with the Pearson index to understand what is the correlation between two set of data. The Pearson correlation index is defined as (where x is the answer of first question and y is the answer of the second question that are under investigation):

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \qquad (2)$$

For example, for what concern the Mobility Attitudes the average daily mileage and the average time spent in the car are analyzed. The r-index coming from our data was 56% and so:

- About one half of the interviewed spent inside the car an amount of time proportionate with the kilometers routed.
- Is possible to divide the second half in two more categories,
  - ➢ Short journeys with long time, attributable at traffic jams.
  - ➢ Long journey with short time, attributable to highway paths.

To calculate the weight of each parameter the formula adopted is:

$$weight\ index_j = \frac{\sum value\ answer_i \cdot \#\,respondents_i}{\#\,interviewed\ \cdot \#\,questions \cdot 7} \qquad (3)$$

6. Result Analysis

In Figure 2 (*Part a* and *Part b*) is reported the filled Scoring Matrix. It is possible to see that the highest value has been reached by the dynamic wireless recharge system, also if the gap among the four possible solutions is not so large. However, it is possible to find further advantages for wireless charging:

- This solution reduces more the weight and volume needed on board for the storage system. The reduced weight affects also the vehicle overall efficiency.
- This solution keeps the electricity storage system independent from the recharge infrastructure. It is a key issue to keep the independence: storage systems are relatively new technologies and should be changed in the future. So it is not convenient to invest in an infrastructure that will negatively affect the storage system development.
- The wireless charging system is the one with the highest "Delighters" values, especially the "City Planning" ones. This aspect is very interesting because it will positively influence the end user new technology acceptance.

The three arguments reported above strongly support the idea to adopt the wireless charging system for urban mobility.

Categories	Families	Indicators	Weight	Best if
Technical	Feasiability	€/Wh	0.65	↓
		Kg/Wh	0.40	↓
		l/Wh	0.40	↓
		Storer life cycle	0.50	↑
		Vehicle life cycle	0.40	↑
		Dangers	1.00	↓
		Cost of infrastructure	0.65	↓
	Upgradeability	Traction independent from storage system	0.30	↑
		Reuse of infrastructure if technology changes	0.30	↑
	Enviroment	WTW index	0.60	↓
		Possibility of using renewable primary energies	0.60	↑
		End life disposability	0.60	↑
		Noise	0.60	↓
Customer	Satisfaction	Autonomy	0.53	↑
		Vehicle cost	0.65	↓
		Management costs	0.63	↓
		Reliability	0.68	↑
	Delighters	Accessibility in "green areas"	0.26	↑
		Free parking	0.43	↑
		Performances	0.37	↑
		Discounts/Incentives	0.79	↑
	City Planning	City Invasiveness	0.42	↑

Fig. 2 - Filled Scoring Matrix - *Part a*

Alternatives to be evaluate			
I.C.E.	Fuel Cell	Battery changing station	Dynamic
3	2	3	3
2	3	2	3
3	1	2	4
5	5	2	4
4	4	4	4
3	2	4	5
4	3	3	3
1	2	3	4
2	2	3	4
2	2	3	3
2	4	3	3
4	3	5	3
2	4	4	4
4	3	3	4
3	2	2	3
3	3	3	3
4	3	3	3
3	4	4	4
1	3	5	5
4	3	3	3
2	2	3	3
2	2	2	5
41	40	45	52

Fig. 2 - Filled Scoring Matrix – *Part b*

7. Discussion on Scoring Matrix results

Any structured approach could not be able to manage a large number of parameters that have to be taken into account when assessing complex problems such as mobility. For example, the Axiomatic Design application could lead to a large number of matrices that could be all somehow decoupled, and so impossible to calculate the less information content solution. Scoring Matrix approach overcomes this issue, but for a detailed design it is a too general method, contrarily to Axiomatic Design. In next paragraph, a strategy to overcome the wireless charging technology issue using the Axiomatic Design method will be presented. In this sense, Scoring Matrix and Axiomatic Design are two designing tools that necessarily have to work together.

8. Wireless charging: issues and solutions

Wireless charging technology is one solution to overcome the range limitation of electric vehicles; however, it still has some constraints. Most important are the limitation of vertical distance and lateral misalignment in order to keep the energy transfer process as efficient as possible. In this paragraph, the decomposition tree has been proposed in order to define technical issues and possible solutions. Then, the information content axiom has been used to understand which of the proposed solutions is the most suitable for the city of Firenze characteristics and needs.

8.1. Decomposition tree

In this paper, an integration between the Scoring Matrix and the Axiomatic Design is proposed. The decomposition tree input, and so the Axiomatic Design input, is the technology chosen with the Scoring Matrix approach. It means that the first Functional Requirement of the decomposition tree is the Scoring Matrix output, named in this paper "Scoring Matrix optimal mobility solution", that is in this case study the "Wireless charging strategy". So the two methods joins here: this method can be used as a preliminary study when it is necessary to choose between large number of alternatives and a large number of variables. The Axiomatic Design will be the further step to determine the best possible solution. With this assumption, the decomposition tree is reported here below. It is important to add that the "Vertical Misalignment" is something related to the physics of the inductive magnetic field in resonance and so it has been eliminated from the study.

FR1: "Scoring matrix optimal mobility solution";
DP1: Wireless charging technology;
FR11: Vertical distance (not assessed, technological issue);
FR12: Lateral misalignment;
DP11: (coming from FR11, not assessed).
DP12: System able to decrease lateral misalignment influence on efficiency losses;
FP121: Aided system;
FP122: Automatic system;
DP121 (from FR121): Reference stripe painted on the street;
DP122 (from FR122): Chasing secondary coil system;
DP123 (from FR122): Automatic guided vehicle.
Alternative DP12 systems are:

- Reference stripe painted on the street;
- Chasing secondary coil system;
- Automatic guided vehicle.

The three alternative have increasing complexity and cost. So the list is ordered considering its likeness. Then, to select the optimal solution is necessary to use the Information Axiom, so it is necessary to evaluate is the system range of the proposed technologies and evaluate if this is compatible with the design range. For the wireless charging, the design range is the ±20cm lateral misalignment limit (80% transmission efficiency). As soon as the list is ordered considering the cost efficiency of the solutions, if the first solution would be compatible with the design range it would be selected. Otherwise the choice will be the second and, as last chance, the third. To assess the system range of the fisrt solution a driving simulator with an electric city scenario has been used: the idea is to evaluate the driving ability of a Firenze inhabitants' set with visual aid street signal

9. Driving simulator experiment

The Università degli Studi di Firenze is equipped with a drive simulator constituted by a car body mounted over six pistons and a large curved screen. A set of computers and projectors simulate and make the driver interact with a driving scenario in order to quickly and safely test infrastructures and new technologies. In addition, the greatest possible adherence to the real-world conditions is guaranteed by an engine sound emulator, small screens over the rear mirrors and fully functional gearshift, steering wheel (Figure 3) and with acceleration feelings.

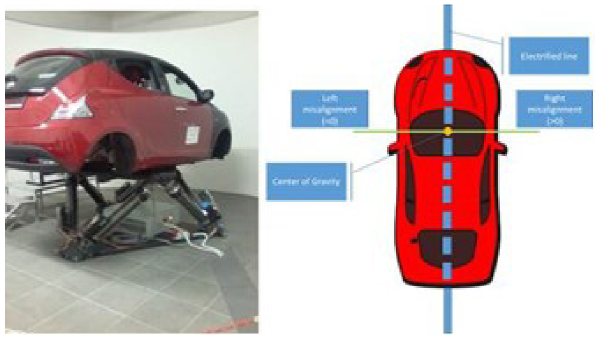

Fig. 3 - (a) Simulator machine and (b) references scheme

For the developed tests, a town scenario has been built. To simulate the wireless recharge infrastructure a blue line was positioned over the road surface. The simulator control software automatically calculates the lateral shift of the car center of gravity from the blue line at 10 Hz.

9.1. The experiment

11 electrified segments have been positioned within scenario and each of the drivers has to follow the path from segment 1 to segment 11. Nine segments were straight and two segments were curved, one to the left and one to the right. Within the city, in addition to a random decided traffic, also a pedestrian crossing and a double-parked car have been introduced to study their interaction with the infrastructure functionality. It has been asked to the tested drivers to behave as normal as possible and to center the blue line, when present, with the car front.

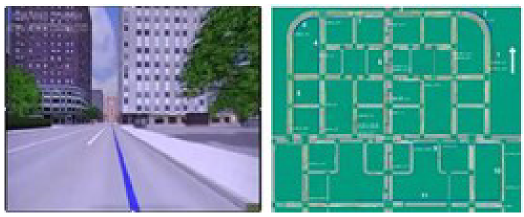

Fig. 4 - (a) Driver view and (b) electric city map

Within the test, two response variables have been considered: driver's precision and accuracy for each of the path segments. More in details, an accurate driver has an average misalignment close to 0 and a precise driver has a low deviation from his average. The best possible, is an accurate and precise driver. More in details, each of the tests gave 11 vectors with lateral misalignment of the driver. The length of each vector is directly proportional to the average speed. This set of data has been considered as a normal distributed set of data with an average (μ) and a standard deviation (σ) value. The μ has been considered as the driver accuracy and the σ as the driver precision. In this way, each of the drivers will have two response variables values, one for precision and one for accuracy.

9.2. Data analysis

The statistical behavior of the drivers has been compared to the system range of the technology to determine if this solution could fit the constraints. As it is possible to see from the Figure 5, the 67% of the travelled road is within the dimensional constraints of ±20cm. In addition, a training analysis has been carried out to determine if the continuous use of wireless charging technology could increase the performance of the drivers. A paired t-test has been carried out where the first record has been the first driving experience and the second record has been the fifth driving experience on the simulator. The paired t-test assessed that there is a difference between accuracy and precision in the two tests with a p-value of 0.000 (accuracy) and 0.006 (precision).

The other decomposition tree "leaf technologies" will not be assessed because this solution is the easiest possible from a design, assembly and maintenance point of view, giving at the same time a good transmission efficiency result.

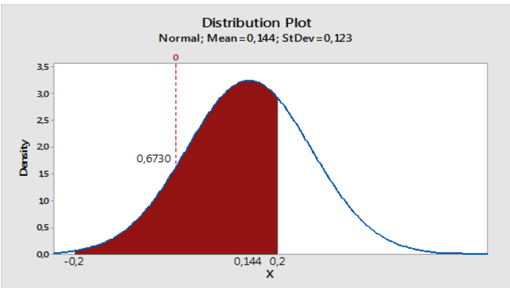

Fig. 5 - Common range

10. Conclusion

Within this paper, the Axiomatic Design method has been expanded with the development a new structured approach to choose between mobility paradigms based on a Scoring Matrix. The new feature introduced by this approach, the possibility to have a screening method strictly related to the Axiomatic Design and directly usable, helps the designer to choose between a large number of solutions managing a large number of involved choosing parameters. This approach has been tested on the Firenze mobility scenario, in order to understand which technology fits better the city and citizen needs. The chosen paradigm has been the wireless charging. At this stage, the Axiomatic Design has been used to develop a strategy to increase efficiency by decreasing the lateral misalignment. A data collection campaign has been carried out with a driving simulator and a set of drivers. The solution of a visual aid has been proved to be the most suitable and economic for the city of Firenze with a common range in the information content analysis of 67%. In addition, an analysis on driver's training shows that the continuous use of the technology could increase much more the alignment performances.

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