A Decision Support System for Robot Selection based on Axiomatic Design Principles

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Abstract

Robotic Systems started to replace the humans in parallel with the development of the robotic technology applications. These robotic systems have complex structure; because they comprise many sub-systems operating in an integrated manner. Therefore, determination of the most suitable industrial robot arm for a production system requires a scientific and systematic methodology. In this study, Axiomatic Design (AD) methodology, which forms a scientific basis for the design and decision-making processes, is employed for the selection of the most suitable industrial robot arm. Based on the literature, the design parameters of industrial robot arms are determined. A decision support system is developed to make the most suitable selection for a certain design by using the information axiom of AD.

Keywords
Axiomatic design, robot selection, decision support system, information axiom.

1. Introduction
The intense competitive environment causes changes in business management concepts, enforces firms to identify and apply strategies in an effort to use production factors more efficiently. In order to provide maintainability, firms start to settle strategies based on price, quality, productivity, rapid response, environmental management, product diversity and flexibility and besides, they begin to use these strategies as competitive weapons as well. Moreover, application of advanced technologies in production systems has become essential. Correspondingly, robotic systems has started to take replace humans in the production area. Robotic systems consisting of several integrated sub-systems have complex structure. Due to this structure, selection of a suitable robotic arm, which is one of the robotic systems design stages, is a difficult and important issue. Therefore, determination of the most suitable industrial robot arm for a production system requires a scientific and systematic methodology. In this study, Axiomatic Design (AD) principles (Suh, 2001) are employed for the selection of the most suitable industrial robot arm that satisfies the functional requirements of a certain design. AD establishes a scientific basis for design; improve design and decision-making by providing the designer with a theoretical foundation based on logical and rational thought processes and tools (Suh, 2001). There are two axioms of AD. The Information Axiom states that the design having the least information content is the best one. Besides, the Independence Axiom requires that independence of functional requirements of a design must be maintained (Suh, 2001).

In this study, the design parameters of industrial robot arms that satisfy the independence axiom are determined based on the literature. A decision support system (DSS) is developed to make the most suitable robot arm selection for a certain design by using the information axiom of AD. The proposed DSS is supported by a new software system which facilitates to determine the most suitable robot among the many alternatives which are included in a prepared database in advance. Moreover, this DSS and the software have been implemented in a pilot study. The rest of the paper is organized as follows: The literature concerned with the robot arm selection and the studies that employed Information Axiom for decision making were summarized in the following section. In Section 3, the proposed Decision Support System for the Robot Arm Selection is explained. Next, the pilot application of the proposed methodology is presented in Section 4. Finally, the conclusion of the study is explained.

2. Literature Review

First, the major studies about robot arm selection were reviewed. Different techniques were used for this purpose. These are Technique for Order Preference by Similarity to Ideal Solution- TOPSIS (Parkan and Wu,1996; Bhangale *et al.*, 2004; Bhattacharya *et al.*, 2005), Analytic Hierarchy Process - AHP (Karsak, 1998; Rao and Padmanabhan, 2006), Graphical Method (Bhangale *et al.,* 2004), distance based approach (Kumar and Garg, 2010; 13], data envelopment analysis –DEA (Parkan and Wu,1996; Karsak, 1998; Braglia and Petroni, 1999; Kahraman *et al.*, 2007), OCRA (Parkan and Wu, 1996), Utility Models (Parkan and Wu, 1996), Case-based Reasoning (Chang and Sims, 2005), Dimensional Analysis (Braglia and Gabbrielli, 2000), Digraph and matrix methods (Rao and Padmanabhan, 2006), VIKOR and ELECTRE methods (Chatterjee *et al.*, 2010). These studies and the techniques employed were presented in Table 1.

Table 1. Summary of the Robot Arm Selection Studies

		Year	AHP	TOPSIS	Graphical Technique	Distance Based Approach	Data Envelopment Analysis	OCRA	Utility Model	Case Based Reasoning	Dimensional analysis	Digraph & matrix methods	VIKOR	ELECTRE
Authors	Parkan and Wu	1996		X			X	X	X					
	Karsak	1998					X							
	Braglia and Petroni	1999					X							
	Braglia and Gabbrielli	2000									X			
	Bhangale *et al.*	2004		X	X									
	Chang and Sims	2005								X				
	Bhattacharya *et al.*	2005	X	X										
	Rao and Padmanabhan	2006										X		
	Kahraman *et al.*	2007					X							
	Kumar and Garg	2010				X								
	Chatterjee *et al.*	2010											X	X
	Kentli and Kar	2011				X								
	Goh	1997	X											

In addition, most of the past studies that employed Information Axiom of AD were reviewed, and summarized in Table 2. All of the studies reviewed employed Information Axiom for the selection of the product, design, production system, supplier or other miscellaneous types of systems. Only a few of them considered independence axiom and the information axiom, simultaneously (Helander and Lin, 2002; Jang et al., 2002; Coelcho and Mourao, 2007; Liang, 2007; Cebi and Kahraman, 2010a). Some of the studies employed information axiom for the production system configuration selection (Babic, 1999; Kulak and Kahraman, 2005a; Kulak et al., 2005; Coelcho and Mourao 2007; Cheng, 2010). However, most of the studies attempted to select the most suitable product design on the basis of AD principles (Helander and Lin, 2002; Jang et al., 2002; Akay and Kulak; 2007; Yucel and Aktas, 2007; Liang, 2007; Cebi and Celik, 2008; Tian et al., 2009; Cebi and Kahraman, 2010a; Cheng and Huang, 2010; Akay et al., 2011). A few of them intended to select the most appropriate supplier by the information axiom (Kulak and Kahraman, 2005b; Ozel and Ozyoruk, 2007; Celik et al., 2009; You, 2011). The rest of the studies have different application areas and cannot be put into these categories (Kulak, 2005; Cebi et al., 2008; Ge et al., 2008; Kahraman and Cebi, 2009; Cicek and Celik, 2009; Celik et al., 2009; Kahraman et al., 2009; Celik, 2009a; Celik, 2009b; Cebi and Kahraman, 2010b). These studies consider either crisp (quantitative) criteria or both crisp and fuzzy (qualitative) criteria. In other words, some studies considered those criteria that cannot be quantified and those that are linguistic (Kulak and Kahraman, 2005a; Kulak et al., 2005; Kulak and Kahraman, 2005b; Kulak, 2005; Ozel and Ozyoruk, 2007; Akay and Kulak, 2007; Yucel and Aktas, 2007; Cebi et al., 2008; Ge et al., 2008; Cebi and Celik, 2008; Kahraman and Cebi, 2009; Tian et al., 2009; Cicek and Celik, 2009; Celik et al., 2009; Celik et al., 2009; Kahraman et al., 2009; Celik, 2009a; Celik, 2009b; Cebi and Kahraman, 2010a; Cheng and Huang, 2010; Cheng, 2010; Cebi and Kahraman, 2010b; Akay et al., 2011).

Table 2. Summary of Studies Employing Information Axiom for Decision Making

	Axiom Used		Application Area				Method			Evaluation Type	
	Independence	Information	Product/Design Selection	Production System Selection	Supplier Selection	Others	AD Application	Hybrid	Theory	Crisp	Fuzzy
Publications											
Babic (1999)		1		1			1			1	
Helander and Lin (2002)	1	1	1				1			1	
Jang et al. (2002)	1	1	1				1			1	
Kulak and Kahraman (2005a)		1		1					1	1	1
Kulak et al. (2005)		1		1					1	1	1
Kulak and Kahraman (2005b)		1			1				1	1	1
Kulak (2005)		1				1		1		1	1
Coelcho and Mourao (2007)	1	1		1			1			1	
Ozel and Ozyoruk (2007)		1			1			1			1
Akay and Kulak (2007)		1	1					1		1	1
Yucel and Aktas (2007)		1	1					1			1
Liang (2007)	1	1	1				1			1	
Cebi et al. (2008)		1				1			1		1
Ge et al. (2008)		1				1		1		1	1
Cebi and Celik (2008)		1	1					1			1
Kahraman and Cebi (2009)		1				1			1	1	1
Tian et al. (2009)		1	1					1		1	1
Cicek and Celik (2009)		1				1			1	1	1
Celik et al. (2009)		1				1		1		1	1
Celik et al. (2009)		1			1			1			1
Kahraman et al. (2009)		1				1		1			1
Celik (2009a)		1				1		1			1
Celik (2009b)		1				1		1			1
Cebi and Kahraman (2010a)	1	1	1						1	1	1
Cheng and Huang (2010)		1	1					1		1	1
Cheng (2010)		1		1				1		1	1
Cebi and Kahraman (2010b)		1				1			1	1	1
Akay et al. (2011)		1	1						1		1
You (2011)		1			1		1			1	

3. Industrial Robot Arm Selection Criteria

In this study, robot selection criteria are classified into two groups as filtering criteria and evaluation criteria. The design parameters which serve as prerequisites or have representational structures are classified as filtering criteria.

The design parameters which allow tradeoffs in determined ranges are classified as evaluation criteria. Industrial robot arm selection methodology has two stages. In the first stage, robot arm alternatives are eliminated by using filtering criteria. Optimum robot arm selection is made by calculating information content of evaluation criteria in the second stage.

3.1. Filtering criteria: Filtering criteria are the criteria, validity of which must be ensured. These prerequisite criteria are:

- *Degrees of freedom (DOF)* is a term used to describe a robot's freedom of motion in three dimensional space - specifically the ability to move forward and backward, up and down, and to the left and to the right (Ross et al., 2011).
- *Protection class* is a term which states durability of protected electrical component of robots towards environmental condition.
- *Connection type of* robot can be *base*, *ceiling* or *wall* connection. It is decided by taking account the facility layout, constraints, obstacles.
- *Nominal payload capacity is* the amount of the maximum load to carry at the maximum speed while preserving the repeatability. When a robot arm is selected, it is required that nominal payload capacity is higher than the products and equipments.
- *Wrist reach distance* states maximum distance which robot arm reaches in the work envelop.

3.2. Evaluation criteria: The evaluation criteria are the criteria whose information contents would be calculated in the assessment process. Some of the evaluation criteria can get all the desired values between the lower and upper limits, because of the programmable structure of robots. In these limits, the probability of success to satisfy the functional requirement (FR) is one. Because the intended destination can exactly be reached between the lower and upper limits depending on the nature of the work. In this study, these criteria are classified as *controllable criteria.* On the other hand, some of the evaluation criteria are not controllable. Due to the nature of system, the values of criteria deviate from the target point. These criteria are given in terms of tolerance and classified as non-controllable criteria in this study.

- *Maximum speed:* Speed of each axis is important for the robot to do the job on the desired time, or quality. Because speed is programmable and can get every desired value under the maximum speed, it is controllable criteria.
- *Repeatability:* Repeatability is a measure of the ability of the robot to move back to the same position and orientation over and over again (Shiakolas et al., 2002). It is maximum error among repeated points and given in terms of tolerance by robot suppliers. It is non-controllable criteria. In this study it is assumed to have uniform distribution.
- *Investment cost:* It mentions the purchasing cost without additional equipments. It is classified as non-controllable criteria.

4. Industrial Robot Arm Selection Methodology Based on Axiomatic Design

In this paper, a robot arm selection methodology based on axiomatic design principle is proposed. The methodology is supported by software and a decision support system is developed. The steps of the methodology illustrated in Figure 1 can be expressed as follows:

- Defining the customer needs: The selection procedure begins with identifying what customer wants.
- Defining the functional requirements (FRs): The FRs should be defined as if they will provide the minimum set of independent requirements that the design must satisfy. In other words, the FRs should be determined based on the first axiom of the axiomatic design, information axiom. These sets of determined FRs contain the ability of lifting of product, accessing points within work envelope, achieving the duty on determined time, the maintainability of robot arm, low investment cost etc.
- Determining the design parameters (DPs): The design parameters corresponding to the FRs in the field of functional domain should be determined. In this study; by reviewing the robot selection literature and interviewing robot supplier, the following design parameters are determined to choose optimum robot arm for the operations: nominal payload capacity, manipulator wrist reach, maximum speed on the basis of each axis, repeatability and cost etc. These parameters are determined by considering the FRs which do not affect each other.

- Classifying the design parameters: The design parameters are classified into filtering criteria or evaluation criteria as mentioned above (section 1). Filtering criteria is used to determine suitable alternatives to satisfy functional requirements in pre-screening process. Evaluation criteria are determined as controllable or non-controllable criteria by considering the definition which robot supplier serves.
- Preparing the database: The database component of Decision Support System (DSS), which is used to speed up selection process, must be formatted according to the model used in the evaluation process.
- Determining the design qualification and design range: By using the interface, the target design specifications and design range of the designer or decision-maker are transferred into the decision support system.
- The start of evaluation process: With the help of the DSS's implication mechanism, the robot arm alternatives in the database are analyzed by considering design specifications and design ranges.
- The process of filtering: The alternatives which are not suitable are eliminated.
- Calculating the information contents: The information contents of the suitable alternatives are calculated by information axiom of axiomatic design. While information contents of non-controllable criteria are calculated with the AD proposed in (Suh, 2001) (See Equation 1), information contents of controllable criteria are calculated with the modified AD proposed by Helander and Lin (2002) (See Equation 2)

$$I_{controllable\ criteria} = log_2\left(\frac{Controllable\ design\ range}{Common\ range}\right) \quad (1)$$

$$I_{non-controllable\ criteria} = log_2\left(\frac{System\ range}{Common\ range}\right) \quad (2)$$

- Selection of robot arm: The optimum robot selection is made according to principle of "the design that has smallest information content is the best design" (Suh, 2001) that is called the Information Axiom.

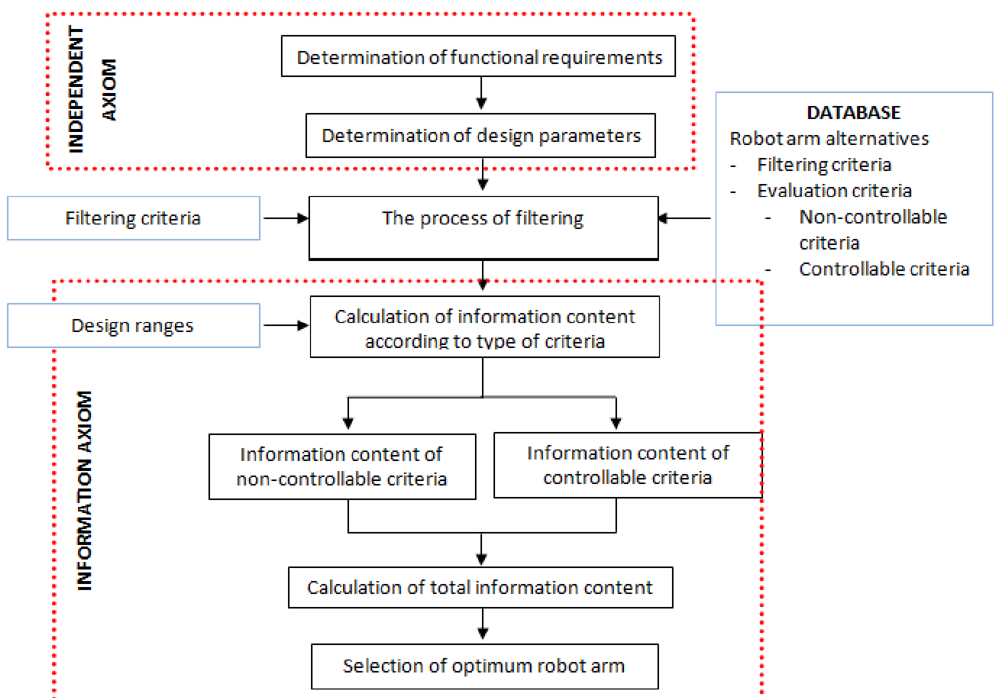

Figure 1: Industrial Robot Arm Selection Methodology

5. Pilot Application

For a pick-n-place application in a manufacturing firm, the following basic requirements are assumed:

- The products with gripper, whose weights are between 0.3 and 0.5 kg together, is required to lift and move.
- Connection type: base
- 4-axis robot arm which has Scara configuration has enough capability to realize the desired duty.

- The robot arm is required to work between 100-200 mm for the desired operation
- The required robot arm speed for each axis:
    - Axis 1: 0-500 degree/s
    - Axis 2: 0-600 degree/s
    - Axis 3: 0-1000 mm/s
    - Axis 4: 0-2000 degree/s
- The acceptable range of repeatability: ±0.02 mm
- The budget allocated for the initial investment cost is no more than 15.000 Euros.

Three alternatives of robot arm which will be taken in the evaluation process that are included in Table 3. These robot arms are the alternatives which are determined as suitable ones through the filtering process.

Table 3. Functional specification and design parameters of Robot A,B,C

	Criteria	Unit	Robot A		Robot B		Robot C		Design	
1	**Degree of freedom**	-	4 axis		4 axis		4 axis		4 axis	
2	**Driver system**	-	Electric		Electric		Electric		Electric	
3	**Control Type**	-	Servo		Servo		Servo		Servo	
4	**Connection Type**	-	Base		Base/Ceiling		Base/Ceiling		Base	
5	**Nominal payload**	kg	0	0,5	0	2	0	2	0,3	0,5
6	**Wrist reach distance**	mm	0	220	0	400	0	600	100	200
7	**Operating speed axis 1**	degree/s	0	867	0	650	0	450	0	500
8	**Operating speed axis 2**	degree/s	0	867	0	725	0	520	0	600
9	**Operating speed axis 3**	mm/s	0	580	0	2100	0	2100	0	1000
10	**Operating speed axis 4**	degree/s	0	2500	0	2020	0	2020	0	2000
11	**Repeatability**	mm	-0,01	0,01	-0,01	0,01	-0,01	0,01	-0,01	0,01
12	**Investment Cost**	Euro	12500	13500	14500	15500	19500	20500	0	15000

The system, design and common range of Robot A operating speed for axis 1 and axis 3 are shown in Figure 2. As it can be seen in this figure, the system range of operation speed of axis 1 compasses the design range of it. It means that the duty can be required to achieve in the design range and every duty can be achieved. So information content for operation speed of axis 1 is calculated as zero. For operation speed of axis 3, every duty cannot be achieved. So the information content is above zero. The probability of the duty which could be achieved is 580/1000. The information content of Robot A operating speed for axis 1 and axis 3 can be calculated as follows:

$$I^*_{A\,(speed\ of\ axis\ 1)} = \log_2\left(\frac{Design\ range}{Common\ range}\right) = \log_2\left(\frac{500-0}{500-0}\right) = 0$$

$$I^*_{A\,(speed\ of\ axis\ 3)} = \log_2\left(\frac{Design\ range}{Common\ range}\right) = \log_2\left(\frac{1000-0}{580-0}\right) = 0{,}79$$

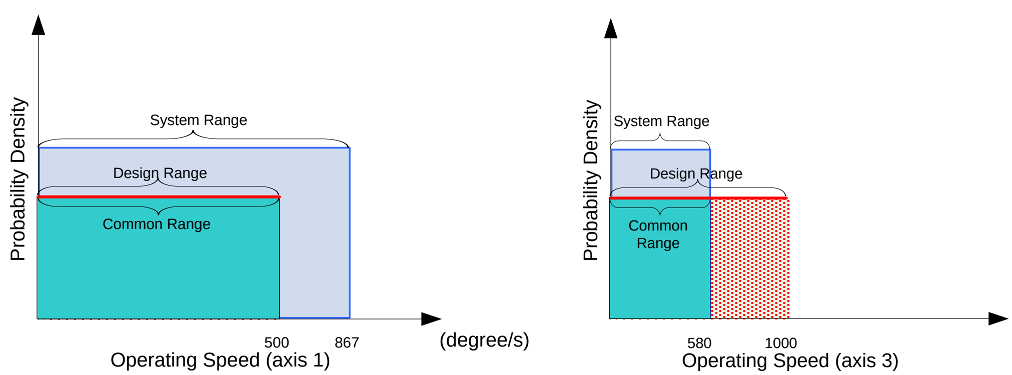

Figure 2: System, design and common range of Robot A operating speed for: (a) axis 1, (b) axis 3

The system, design and common ranges of Robot A-repeatability and investment cost are shown in Figure 3. The design range overlaps with the system range for repeatability. Therefore the robot can satisfy the customer's needs for repeatability. The robot is also successful in order to satisfy investment cost. Because the robot price range is below the price which the customer agrees to pay. The information content of Robot A-repeatability and investment cost can be calculated as:

$$I_{A\,(repeatability)} = log_2\left(\frac{System\ range}{Common\ range}\right) = log_2\left(\frac{2-(-2)}{2-(-2)}\right) = 0$$

$$I_{A\,(investment\ cost)} = log_2\left(\frac{System\ range}{Common\ range}\right) = log_2\left(\frac{13500-12500}{13500-12500}\right) = 0$$

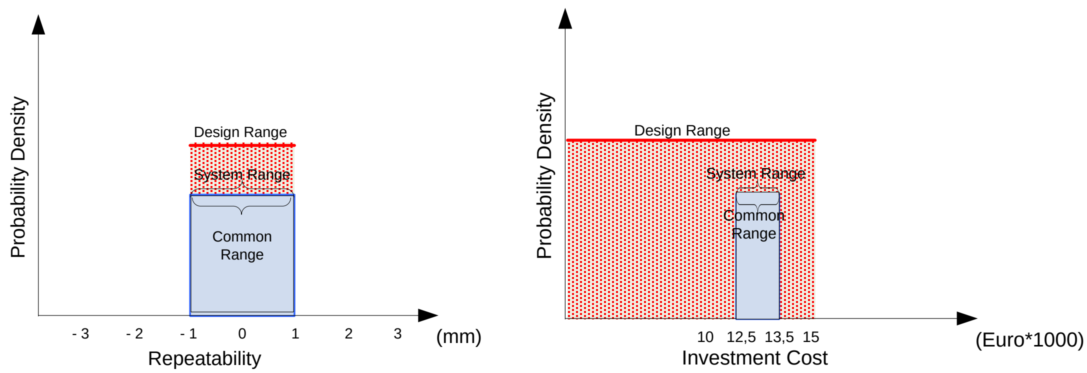

Figure 3: System, design and common range of Robot A – (a) Repeatability, (b) Investment Cost

The total information content of robot is the sum of each parameter's information content. As denoted in Table 4, Robot A with the minimum information content will be chosen as the best robot arm to meet the functional requirement according to the information axiom of axiomatic design. Because Robot C does not satisfy the investment cost range, the information content is calculated as infinite.

Table 4. The Information Content of Robots

	Information Content of Robots		
Parameters/Robot type	**Robot A**	**Robot B**	**Robot C**
Working speed axis 1	0,00	0,00	0,15
Working speed axis 2	0,00	0,00	0,21
Working speed axis 3	0,79	0,00	0,00
Working speed axis 4	0,00	0,00	0,00
Repeatability	0,00	0,00	0,00
Investment Cost	0,00	1,00	infinite
Information Content	**0,79**	**1,00**	**infinite**

By using MATLAB software, the decision support system based on the methodology is developed and utilized to evaluate a large number of alternatives more rapidly. An interface of the DSS is presented in Figure 4.

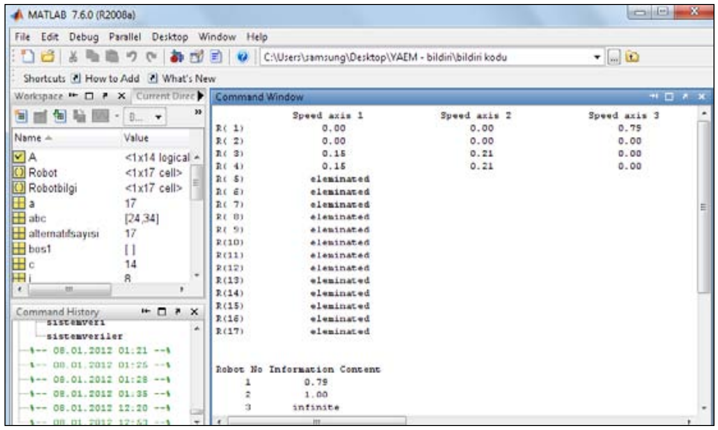

Figure 4: An interface of the DSS in MATLAB

6. Conclusion

This paper presents an industrial robot arm selection methodology based on axiomatic design for helping decision maker to select optimum robot arm. By using methodology, more systematic and consistent decision making process has been obtained. In order to evaluate a large number of alternatives more rapidly, the methodology is supported by software and a decision support system is developed in MATLAB. With the developed decision support system having high data processing and analyzing capacity, large number of robot arm alternatives can be analyzed rapidly. In the study, the use of the methodology is inferred by pilot application and the developed DSS.

In the future study, robot selection criteria could be expanded to include the special purpose application by decomposing robot components in detail. For example, sub-criteria of the components of robot such as controller, actuators, and driver systems can be determined by using independence axiom and included in the selection process.

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