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Designing Efficient Material Handling Systems Via Automated Guided Vehicles (AGVs)

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Abstract

The designing of an efficient warehouse management system is a key factor to improve productivity and reduce costs. The use of Automated Guided Vehicles (AVGs) in Material Handling Systems (MHS) and Flexible Manufacturing Systems (FMS) can help to that purpose. This paper is intended to provide insight regarding the technical and financial suitability of the implementation of a fleet of AGVs. This is carried out by means of a fuzzy set/qualitative comparative analysis (fsQCA) by measuring the level of satisfaction of managerial decision makers.

Keywords

Fuzzy sets, qualitative comparative analysis, autonomous guided vehicles, conflict resolution, decision-making, material handling systems, flexible manufacturing systems.

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1. Introduction

Logistic processes are a key factor in the industrial performance (Sarker and Gurav, 2005), which can be improved with the use of Automated Guided Vehicles (AGVs). They are programmable and driverless vehicles used in industrial applications by means of a communication and navigation system to carry materials around a manufacturing facility (Pillac et al., 2013). The benefits of its use span from more efficient warehousing systems and inventory control, lower labor costs, increased safety and production, to more Flexible Manufacturing Systems (FMS). The latter is because they can easily deal with changes in both products demand and labor force (Fazlollahtabar et al., 2015).

The design of an efficient AGV network system should also take into account the dimensions of the aisles, stacking areas, workstations, and fixed structures on the facility layout.

There are several ways of navigation and guidance technologies of AGVs, which range from physical guide-paths using laser, magnetic tape, optical sensors, wire, to gyroscope based inertial guidance and wireless. The latter provides the advantage that can be easily modified. In addition, the AGVs can connect different points of the facility using unidirectional, bidirectional, multi-lane and mixed systems. There are many traffic control algorithms to tackle the routing and scheduling problems, which cover static and dynamic approaches (Biçer and Seifert, 2017).

In static approaches the route is known in advance, thus hampering the adaptation to changes in both traffic conditions and logistic system. In dynamic approaches the route uses real-time information (for instance, with regard traffic conditions and obstacles) to calculate the route, thus providing calable MHS and FMS (Gourgand et al., 1995).

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2. Methodology

This paper designs an efficient AGV fleet using the fuzzy set/qualitative comparative analysis (fsQCA) (Ragin, 2008). The methodology considers many factors or conditions, covering management, financial and technical ones. The factors or antecedent conditions used in the fsQCA are presented in Table 1. The aim is to determine which configuration of conditions leads to the actors' satisfaction, which cover shareholders, managers, labor unions and workers.

The fuzzy set/qualitative comparative analysis, uses Boolean algebra and fuzzy logic to develop principles of comparison in the qualitative studies of social and economic phenomena (Ragin, 2008; Berbegal-Mirabent and Llopis-Albert, 2015; Llopis-Albert and Palacios-Marqués 2016; Llopis-Albert et al., 2017). An exhausted explanation of the methodology can be found in Mendel and Korjani 2012, 2013.

The methodology is intended to find which combination of conditions (configuration) are minimally necessary and/or sufficient for obtaining a certain outcome (Meyer et al., 1993).

The methodology is applied to small and medium-sized enterprises (SMEs) of several industrial sectors in Spain based on a wide range of information such as reports, surveys and expert judgment.

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Table 1. Factors or antecedent conditions used in the fsQCA.

Factors or antecedent conditions (C)	
Management & Financial	C1: Feasibility of implementing the AGVs system. Investment costs (acquisition and installation).
	C2: Improved productivity and maximization of performance.
	C3: Annual savings.
	C4: Flexibility to changes (e.g., to address possible demand fluctuations and failures in the production line or the AGVs system, restrictions of machines, number of workers, number of shifts, need of manufacturing different products, etc.) in order to achieve FMS.
	C5: Other costs such as transportation, operation, energy and maintenance costs, depreciation, workers' dismissals and training, equipment and software controlling costs.
	C6: Implementation does not lead to layoffs.
Technical	C7: Type of AGVs system (i.e., towing vehicles, unit-load carriers, pallet trucks, fork trucks, and assembly lines).
	C8: Minimum travel times (definition of the optimal path layout, route scheme and facility layout). Optimal allocation of stacking areas, maximizing the space utilization, number and location of load/unload points.
	C9: Optimal number of AGVs (fleet size) to satisfy the demand. Maximum vehicle utilization (i.e., maximum load capacity per vehicle, reduction of empty vehicle travels and idles points). Minimum inventory level.
	C10: Optimal network flow (efficient driverless traffic control schemes): efficient rerouting in real time for collision avoidance, minimum time for loading/unloading and battery-charging, minimum queue length, minimum loading times and reduction of idles points. Standardization of the workflow. Efficient vehicle scheduling/dispatching of operation tasks. Level of computerization for controlling the network flow and the complexity of its use.
	C11: Guidance technologies (i.e., colorful and magnetic lines, optical sensors, laser navigation systems, magnet and gyroscope based inertial guidance, and wireless technologies).
	C12: Vehicle maneuverability (i.e., steering angles and axis, vehicle degrees of freedom, number of motors, acceleration and rotation). Vehicle trajectories (i.e., U-turns, curve or sharp turns or free-ranging movements).
	C13: Other technical considerations such as safety considerations, easiness of use, energy consumed, ergonomic and ecological considerations.
Outcome	Actors' satisfaction

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The actors' preference degree regarding the conditions is determined using a continuous fuzzy set, ranging from 0 (for low degree of acceptance) to 1 (for high degree of acceptance). These values are obtained based on the available information and after a calibration process. This allows to define the truth table, which is subsequently analyzed by means of the fsQCA software (Ragin, 2008). Because there are 13 factors, so that the matrix dimensions are (2^{13}) rows and 13 columns, which lead to 8192 possible configurations. Table 2 shows the necessary conditions for the actors' satisfaction and also for the negation of those factors, which is marked with the tilde (~) sign.

Necessary conditions have a consistency score that exceeds the threshold of 0.9 (Schneider et al., 2010). Only 2 (C2 and C4) out of 13 conditions show a consistency above the threshold. However, there are other existing conditions in most of the configurations (e.g., annual savings).

This shows that the outcome (stakeholders' satisfaction) depends on a several conditions because of the high heterogeneity of stakeholders with conflicting interests.

Another step is to reduce the number of rows in the matrix, which is performed using the Quine–McCluskey algorithm (Quine, 1952). In this way the matrix is minimized by means of Boolean algebra to obtain a set of combinations of causal conditions, where each of them is minimally sufficient to lead to the outcome. The minimization step is performed through the coverage and consistency values. Table 3 depicts the 13 solutions that are found by the algorithm, in which black circles (●) indicate the presence of a condition, white circles (□) denote its absence, and blank cells represent ambiguous factors (Ragin and Fiss, 2008). The variety of these configurations suggests that they are sufficient but not necessary. Hence, any configuration explains by itself the actors' satisfaction. Additionally, all configurations present acceptable consistency values (<0.80) and raw coverage values.

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Table 2. Analysis of necessary conditions and consistency and coverage values for all conditions

Conditions tested*	Consistency	Coverage
Feasibility & Investment costs	0.818688	0.718891
~ Feasibility & Investment costs	0.522186	0.908204
Productivity & Performance	0.904768	0.708686
~ Productivity & Performance	0.495829	0.857526
Annual savings	0.813995	0.835048
~ Annual savings	0.570353	0.771792
Flexibility	0.904192	0.786975
~ Flexibility	0.415285	0.735227
Other costs (e.g., energy and maintenance)	0.710327	0.694638
~ Other costs (e.g., energy and maintenance)	0.622680	0.900870
No layoffs	0.643229	0.803151
~ No layoffs	0.626162	0.685901
Type of AGVs system	0.716289	0.684688
~ Type of AGVs system	0.487192	0.729732
Minimum travel times	0.624372	0.734157
~ Minimum travel times	0.743806	0.861560
Optimal fleet size	0.554090	0.726872
~ Optimal fleet size	0.797106	0.837744
Optimal network flow	0.837439	0.843767
~ Optimal network flow	0.520600	0.721766
AGVs guidance technologies	0.712802	0.734233
~ AGVs guidance technologies	0.630611	0.848766
Vehicle maneuverability	0.663432	0.765997
~ Vehicle maneuverability	0.721433	0.851066
Other technical considerations (e.g., safety and easiness of use)	0.707619	0.744357
~ Other technical considerations (e.g., safety and easiness of use)	0.643299	0.842963

Table 3. Sufficient configurations of factors for stakeholders' satisfaction

Configurations (C)	Antecedent conditions (factors)													Coverage		Consistency
	1	2	3	4	5	6	7	8	9	10	11	12	13	Raw	Unique	
C1	○	●		●	○	●	●	●	○	●	●		●	0.399393	0.006967	0.934743
C2	●	●	●			●	●	●	○	●	●	○	●	0.446885	0.009705	0.998509
C3	●	●	●	●	○	○	○		○	○	○	○	○	0.296996	0.020048	1.000000
C4	●	●	●	●	○	○	○	○		○	○	○	○	0.319171	0.013411	0.998957
C5	●	●	●		●	○	○	○	●	●	○	○	○	0.297467	0.000962	1.000000
C6	●	●	●	●	●	○	○	○	●	○		○	○	0.361499	0.049536	1.000000
C7	●	●	●	●	●	○	○		●	●	○	○	○	0.303563	0.007653	1.000000
C8	●	●	●		●	●	●		○	●	●	○	●	0.395964	0.001963	1.000000
C9	○	●	●	●		●	●	●	○	●	●	●	●	0.368814	0.000110	0.943961
C10	○	●	○		○	●	●	○	○	○	○	●	○	0.295386	0.015790	0.988313
C11	○	●	○		○	●	●	○	●	○	○	●	●	0.309983	0.025813	0.990662
C12	●	●	●	●	○	●	●	○	○	●	○	●	●	0.367020	0.001607	1.000000
C13	●	●	●	●	●	●	●	○	○	●	○	○	●	0.377512	0.000451	0.999972
Solution coverage: 0.838760																
Solution consistency: 0.956481																

Note: 1. Black circles (●) indicate the presence of a condition, white circles (○) denote its absence, and blank cells represent ambiguous conditions.
2. Frequency threshold = 1; consistency threshold = 0.950909.

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4. Conclusions

Nowadays, the use AGVs are becomingly more common in the manufacturing industries for transport and warehousing purposes. This paper presents a powerful technique, based on the fsQCA, to design efficient warehouse management system and improve productivity and reduce costs.

The method has been successfully applied to a real case study of small and medium-sized enterprises (SMEs) of several industrial sectors in Spain. It can help the decision-making process when designing and implementing a network flow of AGVs systems. Results show that actors are more interested in management and financial conditions than in technical ones. Nevertheless, shareholders and managers pay more attention to the achievement of profits, while labor unions and workers are more prone to keep their jobs and concerned about the technical factors that can hinder the MHS and in safety issues. The unique necessary conditions are the improvement of productivity and performance and the attainment of FMS, since they presumably favor all stakeholders.

The methodology increases the business performance and leads to flexible manufacturing systems that can quickly reconfigurable due to production changes. Moreover, it provides more agreement among stakeholders, thus reducing possible delays in the implementation of the AGVs system because of work union strikes.

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