Smart and Flexible Manufacturing Systems using Autonomous Guided Vehicles (AGVs) and the Internet of Things (IoT)

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Technologies such as Autonomous Guided Vehicles (AGVs) and the Internet of Things (IoT) increasingly disrupt traditional manufacturing and production systems. However, there is a scarcity of empirical studies synthesising and evaluating the impact of disruptive technologies on existing manufacturing systems. This study examines the impact of AGVs applying IoT on Flexible Manufacturing Systems (FMS) through a case study demonstrating the integration of AGVs with IoT in a manufacturing company. As a concept, FMS was conceived decades ago; this study uses socio-technical systems theory to elaborate the concept of FMS into the current context. Key themes uncovered from the literature review include (i) AGVs in warehouse systems, (ii) AGV scheduling and routing, (iii) Human-machine interface, and (iv) integrating and controlling AGVs/IoT. The case study demonstrates how AGVs can create smart, flexible manufacturing systems by taking the following steps: (a) problem identification, (b) performance measurement, (c) designing the proposed solution, (d) evaluate IoT systems, (e) implementation of the new solution, and (f) future improvements. The study concludes with specific recommendations to implement Industry 4.0 in manufacturing companies.

Keywords: Autonomous Guided Vehicles (AGVs); Internet of Things (IoT); Flexible Manufacturing Systems; Smart Manufacturing, Industry 4.0; Case Study

1 Introduction

Industry 4.0 is an umbrella term that refers to the increasing digitisation and automation of manufacturing environments, advanced robotics, and autonomous systems, which increasingly revolutionise traditional production and manufacturing systems (Koenigsberg and McKay 2010; Wieland, Handfield, and Durach 2016). Industry 4.0 as a concept was originally conceived in Germany in 2011 to build the direction of Germany's economic policy based on new technological innovations (Mosconi, 2015).

However, soon Industry 4.0 was widely accepted to define the digital transformation of manufacturing systems worldwide (Liu, Zheng, and Xu 2021). Industry 4.0 technologies, such as Autonomous Guided Vehicles (AGVs) and the Internet of Things (IoT), disrupt traditional manufacturing and industrial practices toward flexible manufacturing systems with enhanced productivity and efficiency (Wagner and Walton 2016). However, few empirical studies have synthesised and evaluated the impact AGVs and IoTs on Flexible Manufacturing Systems (FMS) (Schwab 2016).

As a concept, the Flexible Manufacturing System (FMS) has existed for several decades, e.g., Browne et al. (1984) defined it as "*an integrated, computer-controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of part types*". Initially, Buzacott and Yao (1986) described an FMS as consisting of five parts: i) a set of machines or work stations, which have some degree of flexibility, such as that they do not require significant set-up or change-over time; ii) a Material Handling System (MHS) that is automated and flexible so that jobs can move between any pair of machines of flexible job routing; iii) a network of supervisory computers to manage job routing, track job status, and communicate instructions among relevant parts; iv) monitoring operational performance and alerting problems; v) the jobs to be processed by the system. However, Industry 4.0 technologies profoundly impact all parts of FMS; for example, AGVs affect the material handling system, and IoT affects the job supervising monitoring of performance and job routing. However, how AGVs impact FMS design, operations, and control is largely unexplored, theoretically and in practice.

This study examines the impact of AGVs on flexible manufacturing systems through a literature review and a case study of AGVs/IoT implementation in a flexible manufacturing company.

This study makes the following contributions:

1. Following a literature review, it reveals four key themes in the literature relevant to AGV implementation in flexible manufacturing systems: (i) AGVs impact on warehousing management, (ii) Scheduling and Routing of AGVs, including synchronising RFID with AGVs, (iii) Human-Machine Interface, and (iv) AGV/IoT integration.

2. Based on an in-depth case study examination on AGVs/IoT integration in a manufacturing system, this study proposes a system design for smart, flexible manufacturing systems based on the following steps: (i) problem identification, (ii) performance measurement, (iii) designing the proposed solution, (iv) evaluate IoT systems, (v) implementation of the new solution, and (v) plan future improvements.
3. The study uses the socio-technical systems to theorise the concept of flexible manufacturing systems: the advent of Industry 4.0 technologies and mega-trends such as post-pandemic disruptions and geopolitical crises call for applying the concept of FMS in the new reality: despite socio-technical systems theory has used in empirical investigations of manufacturing environments.This study is the first to elaborate this theory to the FMS context.
4. Based on the findings from the literature review and the learnings from the case study implementation, the study recommends specific actions to create smart, flexible manufacturing systems, including (i) gathering relevant data to assess technology impact for the specific company, (ii) calculate current AGV workload, (iii) analyse process delays, (iv) improve manufacturing flexibility by enhancing human-machine automation interactions, and (v) adopting system thinking to sustain flexibility as a system's property.

The paper is organised as follows. Initially, the background of the study and the literature review are presented in Sections 2 and 3. The research design presented in Section 4 presents the case study and the proposed solution to an example of AGV manufacturing problems. The final Section 5 concludes and explains the contribution of this study, managerial implications, limitations, and recommendations for future research.

2 Background and Motivation

Industry 4.0 describes the transformation of existing factories into smart manufacturing systems, yet it is unclear how existing flexible manufacturing systems can benefit from disruptive technologies like AGVs and IoTs. Most of the literature on FMS has focused on flexibility itself (Mendes and Machado 2014), and less attention has been paid to the FMS concept. This study adopts a systems approach to investigate how AGVs impact flexible manufacturing systems' design, operations, and control. Specifically, it assumes FMS as complex socio-technical systems (Soliman, Saurin, and Anzanello 2018; Baxter and Sommerville 2011) where the introduction of advanced technologies (AGVs, IoT) has a profound effect on their performance (Flexibility). The effect is realised via improved operational efficiency, enhanced human-machine interactions, and better system control.

An Automated Guided Vehicle (AGV) is a driverless material handling system initially introduced to move commodities several decades ago. However, its use evolved into several indoor and outdoor applications (Ivanov et al., 2020). For example, AGVs are found in manufacturing, distribution, transhipment, ports, and transportation (Polten and Emde 2021). AGV's first grand-scale industrial application began in 1974 at a Volvo plant in Sweden (Ullrich and Kachur, 2015). Over a decade later, over 3,000 factories worldwide employed more than 15,000 AGVs. One of the largest AGV applications is General Motors' truck assembly plant in Canada which uses over 1,000 AGVs to carry truck engines, bodies, and chassis across the 2.7 million square feet facility (Le-Anh and De Koster, 2006).

AGVs can transport materials between various areas, such as receiving, storing, sorting, and shipping, thus increasing material handling efficiency (Leite et al., 2015). Reports estimate that more than 100,000 AGVs are currently used in manufacturing and non-industrial operations. Demand is expected to grow significantly due to the increase in big data, machine learning, and requirements for social distancing due to pandemic outbreaks (MarketsandMarkets 2017; Antony et al. 2020). AGV systems represent a significant investment for manufacturing companies, with some applications requiring several millions of dollars. AGVs can be categorised into different types, including loading units, forks, mandrels, loading platforms, cargo towing (tugger, tow train), and others. AGVs can use a variety of top-plate mechanisms to transport and transfer a unit load; typically, a custom deck mechanism absorbs the load on the vehicle's top. AGVs can impact Flexible Manufacturing Systems (FMS) at three levels: (i) design level, (ii) operational level, and (iii) control level.

Regarding FMS design, studies have used heuristics, simulations, and other advanced analytical methods to investigate how various configurations of AGVs interact with humans and IoT. For example, Farling, Mosier, and Mahmoodi (2001) introduce a tandem configuration to minimise congestion using simulations that assess AGV performance, and Aldarondo and Bozer (2020) examine alternative design configurations to find the optimal distance AGVs should travel from the time they pick up a pod until they deliver it to a pick station. Similar studies combine multipurpose nonlinear programming with evolutionary strategies to determine FMS design parameters, including the AGV required number, speed, dispatching rules, part type, scheduling, and buffer sizes (Um, Cheon, and Lee 2009). Fransen and van Eekelen (2021) propose finding the lowest-cost path in a weighted geometric graph where the weights represent the AGB's travel distance or time. Azimi and Alidoost (2011) apply the same criteria to design the AGV load parameters (such as the AGVs fleet number, load capacity, processing time, and monitoring strategy) to create efficient material handling within FMS. Maughan and Lewis (2000) note that an AGV can be used as both the materials handling unit and the communications line linking each station to the host controller in FMS design.

Studies at the operational level investigated (i) the AGV routing rules that create greater manufacturing flexibility and (ii) the number of AGV vehicles required to achieve the desired flexibility. Concerning routing rules, several studies rely on heuristics, e.g., investigating AGV's impact on healthcare operations (Aziez, Côté, and Coelho 2022) regarding energy efficiency (Kabir and Suzuki 2018). Typically, improving the overall flexibility of the manufacturing system via AGV routing is decomposed into solving two sub-problems: (a) machine selection and operation sequence and (b) flexible guideway design (Aldarondo and Bozer 2020; Fransen and van Eekelen 2021). Concerning the number of AGV fleet vehicles, Vivaldini et al. (2016), extending the work of Mahadevan and Narendran (1993), develop an analytical method to estimate the minimum number of AGVs required to execute a given transportation order within a specific time window. Zou et al. (2020) use a discrete artificial bee colony algorithm to optimise the material handling process by multiple-AGVs in a matrix manufacturing workshop.

Regarding FMS control, the literature proposes two approaches for routing control: real-time control and a hybrid model. Buyurgan et al. (2007) propose a real-time AGV routing in a random FMS using an evolutionary algorithm-based intelligent path-planning model to demonstrate that this outperforms the traditional dispatching rules for real-time routing of AGVs in many cases. Similarly, Abdelmaguid et al. (2004) developed evolutionary algorithms (a hybrid genetic algorithm (GA) heuristic method) to address the simultaneous scheduling of machines and the AGVs in an FMS, while

Corréa, Langevin, and Rousseau (2007) introduced a decomposition method to solve the scheduling problem of up to six AGVs. The "select all sent most recently" rule outperformed the other rules and work-in-progress in terms of partial traffic time. The variable and the fixed routing partial priority rules generate significantly higher throughput than the corresponding rule. Maughan and Lewis (2010) demonstrate that control software allows real-time communication between the AGV and peripheral equipment using a standard infrared data link, eliminating hardwiring and network protocols.

3 Literature Review

The literature review has revealed different applications of AGVs in flexible manufacturing systems; the main ones are AGVs in warehousing systems, Scheduling and routing of AGVs; Human-Machine interfaces; AGVs, and the Internet of Things (IoT). Two databases were searched, Business Source Complete (EBSCO) and ABI Inform Complete (ProQuest) and a combination of keywords were used, including AGV AND (flexibl* AND/OR manufactur* AND/OR smart* AND/OR material*). The selected databases provide access to articles related to the topic under investigation and have been used in similar studies (Ghobakhloo et al., 2021; Liu, Zheng, and Xu 2021; Winkelhaus and Grosse, 2019; Zheng et al., 2020). Duplicate results were omitted, and 75 articles were included in the review after reading each article. The thematic analysis uncovered several topics that were classified into themes; topics which are not relevant to FMS (e.g., sustainability) are not reported in this study; the topics relevant to FMS were classified into four key themes: (i) effects of AGVs on warehouse design, (ii) Scheduling and Routing of AGVs including synchronising RFID with AGVs, (iii) Human-Machine Interface, and (iv) AGV/ IoT integration.

3.1 AGVs' impact on warehousing management

In warehouse management, it is critical to appropriately organise space and equipment to ensure a manufacturing process's efficiency and quality (Slack and Brandon-Jones 2018). Warehouse management aims to sort production equipment and machinery, save storage space, and create routes for moving (and removing) material, products, and semi-finished goods. Various types of vehicles are used to distribute and collect materials for production machinery. Non-automated vehicles are summoned on command when needed; however, they also encounter disadvantages such as machines standing idle and under-utilising vehicles, thus resulting in the poor system working efficiency (Gould and Colwill 2015). AGVs have several advantages over fixed material handling equipment such as forklifts and conveyor belts, including flexibility, space utilisation, safety, and total cost of ownership (Gademann and van de Velde 2000). For example, AGV systems offer high flexibility to manufacturing systems since they can change channels (or guide paths) in minutes. Wire-guided vehicles can also re-route on command to accommodate changing priorities within an existing system (Vis 2006).

However, these advantages depend on the specifications of AGVs, which differ per manufacturing environment. AGVs are typically utilised for requests requiring longdistance material transportation to multiple destinations or repeated tasks (Ferrara, Gebennini, and Grassi 2014). Another use is relative to delivering raw materials and supporting the automatic movement of work in progress. Work-in-progress can be considered the work between the production line's manufacturing and the finished product's transportation (Roodbergen and Vis 2009). AGVs support the processing and handling of the entire facility, for instance, assembling, kitting, shipping, preparation, warehousing, order picking, just-in-time delivery, and load shifting (Lee and Murray 2018; Dai and Lee 2012).

3.2 Scheduling and Routing of AGVs

AGV scheduling and routing have received significant attention in the past few decades. Scheduling and routing techniques are often interconnected for best warehouse results, such as applications involving many activities (Qiu et al. 2002). The routing's mission is to identify the optimum route and provide a definite destination path for the AGV from its origin to its destination based on the current traffic situation (Martínez-Barberá and Herrero-Pérez 2010). Scheduling involves allocating resources to tasks over time in a decision-making process that takes as the objective function the minimisation of time travelled and cost considerations, given various constraints such as existing resources, current operations, and other managerial goals (Rubrico et al. 2006).

The AGV's controlling algorithms rely either on centralised or decentralised approaches (Martínez-Barberá and Herrero-Pérez 2010). Centralised control is when a single AGV executes all the necessary assignments, such as mission scheduling, route planning, and travel coordination. In contrast, decentralised control refers to a distributed network system giving the AGV a programmed autonomy to operate without the commands from central control.

An AGV network is best depicted as a map containing nodes associated with a series of arcs. An AGV travelling through the network arcs requires a specific cost and time. This map serves as the primary input to the routing algorithm (Co and Tanchoco 1991). However, these common path topology algorithms treat routing problems as the shortest path problems. This is confusing to trace a node and an arc, especially when time is limited (Qiu et al. 2002). In addition, certain restrictions are imposed, leading to the omission of the optimal solution. This can result in a failure or delay in determining a viable route. These algorithms are suitable for small AGV fleets and small route networks (Qiu et al. 2002).

On the other hand, acceptable solutions such as single or multipath, segmented paths and meshes (such as collisions and bottlenecks) are easily removed for certain path topologies, making routing easier to manage. However, these algorithms are highly dependent on the parameters of the manufacturing factory and are not easily replicated. Routing is either static or dynamic (Hodgson et al. 1985). Static routing means that the path of the AGV is predetermined, while in dynamic routing, the AGV can choose different paths between two nodes. A fundamental routing problem is when conflicts occur in the process. Rear-end collisions should be prevented, and the flow of AGVs entering the intersection should be regulated (Egbelu and Tanchoco 1984). (Koff 1987) recommends area control as the most famous and trustworthy method to prevent AGVs from entering another area already occupied by AGVs.

In addition, AGV latency can be reduced by implementing a heuristic approach that reduces the frequency of AGVs that encounter intersections. The ideal situation with zero intersections is a circular or single loop layout (Co and Tanchoco 1991). In a typical system with few intersections, the AGV will autonomously track the route, yet for complex layouts, traffic management control is more demanding (Bose 1986). For example, Narasimhan (1999) analyses routing interruptions and proposes the redirection of AGVs using route databases to capture previously established paths to redirect the AGVs quickly. Re-routing can be based on the following 'rules of thumb':

a) "key aisles" (especially long aisles), where interruptions will significantly affect the manufacturing operations; therefore, these aisles should be specified for AGVs only and not for personnel,
b) When AGVs "tail" each other, the possibility of a deadlock increase and a production interruption would occur,
c) in case an interruption did happen, then the command personnel should check the route database to find an alternative route; this rule is also easily programmable to avoid human interaction, which could delay the process,
d) the more the AGVs, the more likely interruptions would occur frequently; a large number of AGVs indicates an increased demand for AGVs; thus, the less flexible the manufacturing systems become.

Additionally, Martínez-Barberá and Herrero-Pérez (2010) demonstrate that topological and grid-based maps, which can be deployed rapidly, help avoid obstacles during AGV routing and suggest them for companies with limited manufacturing spaces, e.g., small and medium enterprises. Scheduling AGV movements helps predict their traffic flows, avoid congestion, and plan their release from their last location, which shortens their routes and allows flexible deployment. Taghaboni and Tanchoco (1988) point out that two AGVs should not be used simultaneously on the same route; therefore, routing should be dynamic to avoid collisions. Scheduling of multiple AGVs for material handling in warehouse management is covered in the literature, e.g., Rubrico et al. (2008) propose a hierarchical decomposition of the multi-AGV picking problem and find a positive effect on both throughput and due date satisfaction by reducing the total time required to pick a particular batch of orders.

3.3 Human-Machine Interface

Human Machine Interface (HMI) refers to the safe, harmonious, and cooperative collaboration between humans and robots (Villani et al., 2018). Even if FMS is highly automated, human interference always exists, i.e., in a lean environment where the advantages of automation (high accuracy, speed and repeatability) with employees' flexibility and intellectual abilities. However, in the case of AGVs in FMS, HMI imposes several challenges in terms of safety, collaboration, and co-existence (Cardarelli et al., 2015).

HMI must meet three safety standards. Type A includes essential safety prerequisites applicable to general requirements for machinery. Type B is related to general safety standards. Type C involves personal safety measures for specific types of machinery. For example, when an operator directly contacts the AGV, the HMI should ensure a safe interaction to avoid operator injury, e.g., by correctly outlining an intuitive user interface to facilitate physical and cognitive interaction with the AGV (Villani et al. 2018).

The standard ISO 10218-1/2 also defines the ways humans and robots should interact in an industrial environment (Dietz et al., 2012). Risk assessment is usually a prerequisite of HMI, especially for robots, i.e., AGVs, operating in dynamic environments (Knoop, Pardowitz, and Dillmann 2007). Mainstream HMI literature highlights the need for an intuitive user interface to allow the operators to apply their expertise when interacting with the AGVs, including specialised AGV programming skills (Zoliner et al. 2005). A simple method of programming robots is conventional end-to-end programming based on using the learning pad to move the robot through the required motion cycle by nudging (Villani et al. 2018). However, this method has a drawback: it requires programming every new task, which consumes considerable time and involves significant effort for complex tasks. Therefore, conventional endto-end programming is primarily used in simple AGV operations (Dietz et al., 2012).

Another method that overcomes this limitation is offline programming (OLP), which allows controlling the AGV from a central server station. With this method, HMI can be modelled and simulated by graphically representing and detecting potential collisions before they happen; thus, this method is more suitable for complex manufacturing systems such as FMS (Villani et al., 2018). The drawbacks of this method include its high cost and the special skills required to program AGVs, yet the latest software applications can be less expensive and more user-friendly (Pan et al. 2012). Apart from these two methods, another approach relies on a multimodal interface using probing to improve the human-machine interface (Roitberg et al. 2015); probing refers to sensors allowing robots to mimic employee/operator behaviour in ways that workers require no prior experience in interacting with the robots; thus, working with them becomes more flexible (Cardarelli et al. 2015).

HMI can be further improved using vision recognition; in this case, the AGV robot recognises the gestures and (facial) expressions as programming commands (Zhang et al. 2019). For example, Cardarelli et al. (2015) use a centralised data fusion system called a Global Live View, which integrates 3D image recognition with voice controls to control multiple AGVs. The main advantage of this method is the hands-free control. However, one drawback is that misrecognition of voice commands may lead to production delays, impede efficiency, and raise safety concerns (Rogowski 2012). The latest developments in HMI beyond image recognition are augmented reality and virtual reality programming (Michalos et al., 2016). In augmented reality, the user retains a real-world presence. In contrast, a new digital environment is created in virtual reality, captivating the operator's senses and interacting them with robots in the manufacturing space. In both cases, the operators have the flexibility to use augmented and virtual tools to increase their productivity.

3.4 Integrating and controlling AGVs with the Internet of Things (IoT)

The Internet of Things (IoT) is expected to profoundly impact manufacturing through intelligent tools, the usage of data, and mobile productivity (Heck and Rogers 2014). The IoT can transform manufacturing systems in three ways (Almada-Lobo 2016; Schlechtendahl et al. 2015): (i) automation, (ii) digitisation, and (iii) connectivity, i.e., connecting manufacturing space into an integrated, cyber-physical supply chain.

The IoT signifies that items and objects can be connected, tracked, and monitored, which allows manufacturers to automate their production systems and increase performance (Agrifoglio et al., 2017). One of the prominent applications of the IoT is the optimisation and automation of internal logistics within a factory or manufacturing, including materials handlings. Despite successful applications by bigtech companies (e.g., Kiva robots by Amazon), there is little empirical guidance concerning how to optimise materials and information flows, avoid delays, minimise interruptions, and create synergies between AGVs, IoT, and employees working in the factory (Schulze and Wullner 2006).

FMS modelling using IoT and AGV requires consideration of various related requirements accuracy, coverage, integrity, availability, update rate, delay, price, setup, confidentiality, support, robustness, invasiveness, etc. (Hwangbo et al. 2017). Despite IoT technical complexities, the implementation of the IoT can create significant efficiencies, such as reducing excess inventory, flexibility, faster market response, i.e., agility, and improved On-Time Deliveries (OTD) (Haddud et al. 2017). For example, Jiang and Su (2013) implemented a comprehensive tobacco logistics management platform based on IoT technology and found improvements in service quality and decreased operating expenses. Ding (2013) introduces an IoT-based intelligent warehouse management system that simplifies inventory flow and increases warehouse management automation.

One of the key advantages of IoT is that the big data produced by IoT sensors can be integrated with data from other sources such as ERP (sales, suppliers, finance) either in local servers or in the cloud. Integrating IoT with cloud computing creates the Cloud of Things (CoT), an integrated supply chain system that improves performance, agility, data sharing, and integration (Ratten 2016). Gnimpieba et al. (2015) demonstrate a CoT system combined with GPS for real-time geo-positioning tracking that improves control of joint supply chain tracking pallets and containers. Riege (2003) adopts a bottom-up approach by integrating IoT, RFID, ambient intelligence, and a multi-agent system to create a smart, collaborative, and flexible warehouse management system in a similar application.

IoT can revolutionise the indoor positioning of AGVs in a manufacturing system and potentially improve manufacturing efficiency (Moreira and Mautz 2013). However, the technology providing indoor positioning with less than 1-meter accuracy is currently considerably expensive compared to current manufacturing practices that depend on fixed local infrastructure and mobile units such as AGV (Yang and Yang 2009). Despite the advantages, IoT remains expensive and complex, reducing its diffusion among the majority of manufacturing companies which are small and medium enterprises (Moeuf et al. 2018). In addition, companies raise reasonable concerns about privacy and security since IoT systems may be exposed to vulnerabilities, which, if exploited, may expose companies to risks and jeopardise customers' private data (Lonzetta et al. 2018).

4 Research Design

This study followed a research design with two steps. In the first step, a literature review identified the gaps in previous studies; the review uncovered four key themes and provided insights to guide a follow-up empirical investigation and discussion of the case results. A literature review is suitable for investigating and exploring the most current application developments in Industry 4.0 and finding their future potential (Liu, Zheng, and Xu, 2021; Winkelhaus and Grosse, 2019; Zheng et al., 2020). The second step is a case study investigation of AGV implementation within a manufacturing company aiming to develop a system design model that can be used in smart, flexible manufacturing systems.

This hybrid approach assisted in informing the key areas of study for the case study in step 2, once the problem was identified via the literature review in step 1. Adopting a mixed-method research design provides the advantages of triangulation and offers opportunities for multi-disciplinary and in-depth system analysis (Ivanov et al. 2020). Case studies have been used in similar investigations where the system design model is described through a case study method (Ciano et al., 2020; Chiarini and Kumar, 2020; Vlachos et al., 2021). The case study is based on established principles (Eisenhardt 1989; Yin 2017) and follows the design approach deemed most appropriate to better understand how operations can be structured to contribute to the systems model (O'Keefe 2017). Therefore, the case study proposes a conceptual design model as a template for AGV applications in flexible manufacturing problems. The case represents how the proposed solution to a specific problem could be enacted in practice (Hevner and Chatterjee 2010; Hevner et al. 2004; Eisenhardt 1989). The proposed design arises from the specific problems which inform the defined example case while ensuring that all aspects of the problem will be captured. Therefore, the design proposed in this study will examine various aspects and propose solutions for specific AGV manufacturing problems (O'Keefe 2017; O'Keefe 2016).

4.1 Findings from the case study

This study examines a real-case implementation of AGVs in a large manufacturing company in the UK (called the 'Alpha' company). Initially, a researcher analysed the current practice in Alpha and measured the AGV performance via a set of Key Performance Indicators (KPIs) such as current efficiency levels, workload, and their variations according to demand. Then, Alpha decided to integrate AGVs with IoT and developed a design plan with six stages (O'Keefe 2017): (i) Problem identification, especially focusing on delays, accidents, and similar issues, (ii) Performance measurement, (iii) Design of the proposed solution, (iv) evaluate IoT systems, (v)

Implement smart & flexible manufacturing system, and (vi) Future improvements, which include recommendations based on initial IoT/AGVs system implementation.

4.2 Problem Identification

Alpha, founded in the '50s in Japan, is a multi-billion global manufacturer employing over 150,000 employees. Alpha strives for flexibility, teamwork, and the latest technology to improve its productivity, ensure the highest quality, and reduce costs to remain a top manufacturer by being one of the largest global machine parts suppliers.

Around 2000, Alpha acquired a manufacturing company in the UK and restructured it to produce thermal cooling systems for industrial applications. Alpha operations in the UK span from product design and manufacturing to delivery. Alpha consolidates all operations in a single manufacturing site to provide agile and customised solutions to customer needs. Market reports and developments in Industry 4.0 technologies forced Alpha to evaluate its current operations, ultimately resulting in designing and implementing a transformation of its material handling operations using AGVs and IoT.

4.3 Performance Measurement

Initially, Alpha used a set of KPIs to evaluate the current state of its operations, which also revealed weak points that the AGV introduction would eventually improve. Many KPIs are used in Alpha manufacturing systems; the most relevant for this assignment were Overall Equipment Efficiency and AGV capacity and workload.

4.3.1 Overall Equipment Efficiency (OEE)

Overall Equipment Efficiency (OEE) measures the efficiency of manufacturing operations at various levels, such as machine, cell, departments, and factory levels, which allows the benchmarking of manufacturing processes and units (Stamatis, 2010). OEE is a key metric with roots in Total Productivity Maintenance used in the Japanese industry in 1960; thus, it is also widely used in the Alpha case.

In its simplest form, OEE results from three factors: availability, performance, and quality (Sullivan 2005). Availability is the actual production time over the planned production time, the performance of the current run rate over the ideal run rate, and the quality of the product over the total product. OEE is derived by multiplying availability, performance, and quality; OEE values over 85% are considered ideal. Six losses in equipment or machines reduce OEE: Breakdowns, set-up/adjustments, idle/stops, reduced speed, scrap, and start-up/warm-up loss. OEE can be calculated using the theoretical ideal Cycle Time (CT) over the actual average cycle time achieved, i.e., complete parts run over a specified period of time, regardless of quality:

$$OEE = \frac{Average\ CT}{Theoretical\ CT}$$

4.3.2 AGV Capacity and Workload

The maximum capacity of the AGV is considered to be the entire time the vehicle can be used, that is, the total time available in a day, excluding rest time. In Alpha, a shift consists of 430 minutes, regardless of breaks. This will be considered as maximum work capacity. To calculate workload and the real AGV use, the following equations were used:

$$\text{Boxes per shift} = \sum \frac{\text{Shift Demandi}}{\text{PPBi}} \quad (1)$$

$$\text{Trolley Needed} = \frac{\text{Boxes per shift}}{\text{Boxes per trolley}} \quad (2)$$

$$\text{Loops} = \frac{\text{Trolleys needed}}{\text{Trolleys per AGC}} \quad (3)$$

$$\text{Workload} = \frac{(\sum \text{CTi} * \text{Li})/\text{OEE}}{\text{Total time (Shift)}} \quad (4)$$

$$\text{Real use} = \text{OEE} * \text{Total time used} * \text{Load capacity used} \quad (5)$$

4.4 Design the proposed solution

After identifying that Alpha lagged behind the competition in smart and flexible manufacturing capability, it ran a set of tests to estimate the initial AGV usage and positioning system efficiency.

4.4.1 AGVs - Initial usage and efficiency

Six AGVs are operating on various routes throughout Alpha's factory. These vehicles are tugboats installed throughout the factory and guided by magnetic tape defining a given route. In addition, small RFID tags are placed next to the magnetic tape, and the

AGV reads them, and reports their position, giving instructions on the following command, next speed, rotations, and picking or dropping trolleys.

Figure 1 shows the flows of AGVs 1, 2, and 3. These AGVs work on demand, and production leaders load material requirements with a 3-hour forecast. Logistics selects items from Warehouse An on-demand, loads them into the trolley, and transports them by the AGV. Once the AGV is loaded, the logger will press the start button to send the vehicle to a specific station. This is done using an RFID card placed on top of the AGV. When the vehicle arrives at its destination, it automatically releases the loaded cart and proceeds to an empty trolley picking station to collect the empty carts left there by production. An AGV will transport these empty trolleys to Warehouse A and leave them ready for the next loading and reshipment.

Figure 1 also shows the flow chart of AGV 1, which transfers the stamped parts to the oil cooler assembly line. This AGV runs continuously on the route and does not require someone to press the start button. On the oil cooler assembly line, empty trolleys remain in the picking station, and the KANBAN boards in front of the trolleys are filled with material requirements. This trolley will automatically arrive at the press shop area, where it puts down the empty trolley and picks up the previous trolley that has been loaded according to the last KANBAN instruction. The trolley is then brought to the oil cooler assembly line by the AGV. This process lasts all day, from one area to another.

Figure 1 here

4.4.2 AGVs initial OEE

Table 1 presents the theoretical cycle times of each trip. Table 2 presents an example of the measurement of AGVs efficiency. Table 3 summarises daily observations, including the average OEE, average AGVs time and capacity.

Table 1 here

Table 2 here

Table 3 here

From the data in Table 3, the "Real Use" KPI was calculated by multiplying the OEE with the total time used and the load capacity (Equation 5). The Real use values for AGV1, AGV2 and AGV3 were 21%, 43.3% and 20%, respectively. It is evident that the efficiency of AGVs at UK Alpha was much lower than expected.

4.4.3 AGV Positioning assessment

The data obtained from the positioning system was mainly raw information indicating the X position, Y position and Ti. Table 4 summarises the results from the positioning tests for AGV 1.

Table 4 here

Positioning analysis reveals whether what is physically measured in the factory corresponds to the information collected by the positioning system. This enables continuous improvement of the system without a person controlling the AGV, thus reducing costs within the organisation. Table 5 shows the flow of the current workload calculation that each AGV receives according to its routes and material handling, and Table 6 summarises the results.

Table 5 here

Table 6 here

Such poor performance was not acceptable, and Alpha endeavoured to improve efficiency by reengineering AGVs workloads and using IoT to control current and future material handling operations.

4.5 IoT system evaluation

Alpha evaluated several indoor positioning systems to cover the AGV area. Three different technologies were mainly evaluated: (i) Ultra-wide band, (ii) Bluetooth beacons and (iii) Wi-Fi / ESP Wi-Fi___33. IoT solutions were compared against eight criteria: (i) the technology used, (ii) the IoT accuracy, (iii) power source, (iv) tag's battery life, (v) data extraction capabilities, (vi) total cost, (vii) the extra (marginal) cost of adding another AGV to the system, and (viii) the annual maintenance cost including software subscription.

The comparison of IoT positioning systems resulted that the best solution being *IoT6*. This solution comes from a company that provides industrial UWB indoor positioning solutions and offers an adaptable wireless test KIT that can be used to simulate the system before actual implementation. This IoT solution also tracks all moving targets, including forklifts, tools, and vehicles. This information will be possible to improve productivity, reduce risks, and understand AGVs' movements inside the factory. With the test kit, it is possible to define a maximum area of 2500 m^2 and test the systems under different installation conditions. In so doing, it is possible to design the system, simulate its operations, and test the performance of different configurations inexpensively and quickly.

Table 7 here

The IoT solution was tested before implementation. Ten IoT anchors were installed in different positions with a distance lower than 20 meters between anchors. This positioning created a grid of squares capable of tracking and measuring the actual movement of AGVs in real-time (Figure 2). After trial and error, anchors were put closer together since the highly metallic machine condensed areas disturbed the IoT signals (Figure 3). Figure 4 shows how IoT was positioned within Alpha to cover all areas AGVs were operational. The anchors were placed about 20 meters apart, and the area they contain is the vehicle's route.

Figure 2 here

Figure 3 here

Figure 4 here

4.6 Implement smart, flexible manufacturing

After installing IoT, Alpha runs several experiments to demonstrate the improvements by controlling AGV with IoT technologies. These experiments demonstrated that several KPIs were improved, including (i) Unattended material, (ii) AGV errors, and (iii) AGV-Personnel interaction. By improving these KPIs, the overall efficiency was also increased.

4.6.1 Unattended material

When the AGVs moved and stopped in the grey zone, no worker was responsible for them. The grey zone covers machines shared among internal logistics, manufacturing, process engineering, Total Industrial Engineering (TIE), and maintenance departments. 68% of delays were caused by unattended equipment in the aisles of the grey area, forcing AGVs to stop due to their safety sensors to avoid a collision. Whenever AGVs became inactive in a grey area, no workers are responsible for removing unattended equipment and starting AGVs operating again. To solve this problem, new rules are required to cover unattended material in grey areas.

Team leaders, experienced operators in charge of each production line, should have more responsibilities, including material filling, machine stoppages, and daily production planning. For example, The Oil Cooler (OC) and Press Shop (PS) leaders are responsible for the OC-PS AGV for ensuring that it is in operation at all times and for checking that no materials are left behind on the track, that the front truck has been retrieved, and that the vehicles empty trolleys are left when picking up the goods at the terminals. IoT also requires team leaders to be adequately trained to be responsible for AGV in the factory; Alpha should use these new team leaders' skills to improve its operations' flexibility.

4.6.2 AGV errors

The AGV occasionally made long loops in the press shop to drop the trolley. Each time this long loop is created, one minute is lost in total cycle time, resulting in a delay of 13%. Also, sometimes the AGV will make the wrong turn, causing delays on its track and all other tracks. These false turns were due to incorrect information on the trolleys where the AGV should go with no trolley attached. IoT feeds data to the IT department to re-programme the AGV routes depending on actual usage and current track layout. This way, AGVs would stop in case no trolley is attached to them. IoT is expected to eliminate such AGVs' errors to zero.

4.6.3 AGV-Personnel interaction

Most workers at Alpha were not trained on how to operate AGVs, especially when there was a need to interact with them, i.e., they block its route or AGV crossed with a forklift etc. Initially, it was not possible to train everyone on what to do. Therefore, in the first stage, a common scenario is that the AGV is stopped due to unattended materials or even forced to prevent the AGV from loading, and the workers just pass by them. AGVs have a safety sensor in their front part; they will not move until all obstacles are removed. However, untrained personnel tried to run the AGV but waited in front of it to see if it moved. IoT improves AGV-Personnel interaction for all workers. Specifically, IoT can generate data on AGVs stopped or moved unexpectedly. Then, a report can be sent to employees to raise awareness and improve their interaction with AGVs. Further, signs or other visual aids on the top of the AGV and the sides of the trolleys can complement the explanation of basic use and procedures.

4.6.4 Workload improvement

The initial workload of AGVs was very low. To increase AGV efficiency, AGVs were expanded to transport parts initially manually transported from Press Shop to Oil Coolers. This also frees time from employees to allocate to other tasks. AGV also carried gallery Plates, Bottom Plates, and Spacers. Another problem that arose by manually transporting the gallery section was identified, and Alpha ran simulations to resolve it. Initially, the gallery plates were loaded from the punching machine into large wooden boxes or plastic boxes to facilitate transportation from the punching shop to the oil cooler assembly line. Then, these gallery panels must be transferred to the small plastic boxes initially considered. These small boxes are suitable for assembly stations. If an AGV is used, the worker of the punching machine will directly load the channel plate into the small box, which will be suitable for the assembly machine of the oil cooler. In this way, manpower time is reduced, and the whole work is improved. Specifically,

- Gallery plates are being transferred in bulk from the Press Machine to containers and manually sent to the Oil Cooler line.

- Subsequently, the gallery section was transferred to a smaller box suitable for production facilities.

- By transporting the gallery plates with AGV, a double handover is avoided, which reduces the time required for the operator and the quality risk

Thus, the workload increased from 30% to 56%. The savings from this improvement will be the total time workers need to move parts from the Press Shop to the Oil Cooler and the time required to transfer additional material from the large box to the small boxes.

4.7 Future improvements

After the successful implementation of smart, flexible manufacturing technologies, Alpha continued to test various process improvements. They include (i) Route/scheduling optimisation, (ii) unattended material elimination, and (iii) full-scale IoT/AGV implementation.

4.7.1 Route/scheduling optimisation

Different methods could be used to optimise a system, such as metaheuristics, linear programming, and simulations to improve path optimisation and delivery schedule. Due to the need to have small gains and fast results by AGV/IoT integration, a metaheuristic optimisation was left for a later stage. However, experts have been contacted to develop a simple algorithm that the company can use to increase the AGV system's productivity and further reduce costs.

This algorithm aims to increase the number of trips an AGV can make and reduce the amount of inventory that must be left behind at each production station. By doing so, the space requirement will decrease, allowing the company to improve its space and production. In addition, the company operates in a manner similar to a batch-size one system that optimises the entire system and reduces costs, risks, and time. This feature takes into account three constraints: the speed at which the AGV travels (25 meters per minute), the limitation of the AGV moving to only one station instead of multiple stations, and the production speed of each production line.

4.7.2 Unattended material elimination

As a future implementation, the ANDON solution could be used, in which the team leaders are notified of any stop and informed of the coming AGV. In this way, they can solve any problem and remove and place the corresponding carts in the stations. The Andon system aims to apply lean practices as it is designed to facilitate and stimulate partnerships between different categories of workers in the organisation's workforce when discussing problems and making decisions.(Silva and Baranauskas, 2000; Flinchbaugh, 2016). A simple board can notify the oil cooler and press shop team leaders of AGV delays to resolve inconveniences quickly, as follows:

- **Basic function**: If the AGV takes longer than the theoretical cycle time, an alarm and a red light will provide notification of a delay in the delivery system.
- **Next delivery display**: By publishing the expected next delivery time, the team leader will know that they must remove the previously empty trolley and should place the newly loaded trolley. The board can be connected to a tracking system to connect the AGV status to the displayed warning.

4.7.3 Full-scale IoT/AGV implementation

Alpha's ultimate goal is to cover the whole manufacturing space and integrate it with the AGV material handling system. The current system is easily extensible and requires little investment to add additional vehicles to track. In full-scale mode, Alpha can collect all the data required to understand all parameters of the AGVs system. Assets that may be controllable include AGVs, forklifts, tools, and other moving objects, as well as people. Tools like IoT allow Alpha to understand and track several different characteristics of factory movements. Figure 5 shows the anchors that need to be installed throughout the factory to track all movable objects in the area. This requires a total of 170 anchors and the required tags for each item under control.

Figure 5 here

5 Discussion

Industry 4.0 represents an industrial paradigm shift forcing companies to redesign their business models and reconfigure their operational structures to integrate new automation systems within existing operations (Koenigsberg and McKay 2010). The design and integration of Industry 4.0 technologies require novel business models that integrate these innovative technologies with existing manufacturing practices and engineering processes to increase efficiency, productivity, and competitiveness performance.

This study has conducted a literature review of AGV applications in flexible manufacturing systems followed by a demonstration case study (Geels 2004). The literature review revealed the following key themes of AGV implementation in flexible manufacturing: (i) effects of AGVs on warehouse system design and operation, (ii) Scheduling and Routing of AGVs, (iii) Human-Machine Interface, and (iv) AGV/ IoT integration.

Few empirical studies have considered implementing AGVs in flexible production systems. Previous studies have focused on modelling AGV scheduling and routing from different perspectives (Martínez-Barberá and Herrero-Pérez 2010; Draganjac et al. 2016). However, most articles focus on collisions, interruptions, and bottleneck avoidance and do not cover the latest developments in IoT (Ding 2013; Qiu et al. 2002; Zhang et al. 2019). According to the literature review, AGVs can improve the agility and flexibility of manufacturing systems in the following ways:

- Tandem system configuration reduces production bottlenecks and more effectively deploys workers (Farling, Mosier, and Mahmoodi 2001)
- Combined with new sensor and software technologies, these technologies are very suitable for unpredictable or constantly changing production layouts and dynamic working environments. The proposed solution is to decompose the integrated planning model into two sub-problems at the same time, namely machine selection and operation sequencing and flexible guideway design (Seo and Egbelu 1999);
- independent control of the AGV controller with a job order imposed on it. This way, the system's best manoeuvrability is achieved without interrupting work. (Maughan and Lewis 2000).

5.1 Theoretical contributions

This study makes several theoretical contributions to the flexible manufacturing literature. Empirical findings provide novel insights into flexible manufacturing systems design, operation, and control. Previous studies have predominately theorised manufacturing flexibility as a dynamic capability based on the resource-based view and focusing on specific technologies and applications (Mendes and Machado 2014; Kim, Suresh, and Kocabasoglu-Hillmer 2013), lacking undertaking a holistic, systematic view of the manufacturing environment. Several studies have chosen socio-technical systems to examine Industry 4.0 applications, but none has examined FMS (Soliman, Saurin, and Anzanello, 2018; Baxter and Sommerville, 2011). These studies show that socio-technical systems can provide insights into adopting Industry 4.0 technologies to transform traditional production systems (Baxter and Sommerville 2011; Davies, Coole, and Smith 2017). This study extends the socio-technical systems theory to FMS. A key tenet is the interactions between social and technical components in an integrated system (Vlachos et al., 2021). This study provides findings that the human-machine interactions, e.g., programming AGVs to improve operations efficiency, avoiding blockages and collisions in grey areas, were key in the case company; this finding is consistent with the existing literature that HMI is key to improving system performance (Cardarelli et al. 2015; Villani et al. 2018).

Further, this study uncovers that systems logic should direct all phases of integrating AGVs into FMS, i.e., design, operations, and control. This finding is important since prior studies focused either on system design, e.g., with simulation and optimisation studies (Aldarondo and Bozer 2020; Fransen and van Eekelen 2021), or on operation phase, e.g.., with real-time routing (Aziez, Côté, and Coelho 2022; Kabir and Suzuki 2018)., or controlling phase, e.g., via advanced communication (Maughan and Lewis 2000) (Abdelmaguid et al. 2004). However, adopting the system logic allows one to evaluate and adopt an FMS in different contexts; few studies have evaluated the FMS performance in uncertain or dynamic contexts like the post-covid business environment (Zhang et al. 2019) (Aziez, Côté, and Coelho 2022). Responding to calls for more research and theoretical developments in the Industry 4.0 operations (Ivanov et al. 2020; Ghobakhloo et al. 2021), the findings of this study provide a systematic way to improve FMS performance which, due to its flexibility and adaptability, can be especially resilience in dynamic environments.

5.2 Managerial Recommendations

The concept of Flexible Manufacturing Systems has received renewed attention due to the developments in Industry 4.0 and the urgent need for economies to respond to volatile business environments. This study recommends using AGV and IoT to create smart, flexible manufacturing systems. The following recommendations are proposed for companies seeking to take advantage of these Industry 4.0 technologies:

- **Gather relevant data** early for a period of at least 15 days and compare them with the data obtained by the positioning system. Then, transform the data into processed information to analyse the system performance; tools can be engineering heuristics using trial and error paths, machine learning from the positioning system, and meta-heuristics based on all data available.

- **Calculate the AGV workload** to understand if there is space to transport more products and which routes/stations. The case study achieved 40% AGV workload improvement using these steps.
- **Analyse delays**: in the case study, delays occurred due to common mistakes, e.g., putting a tool on a floor that obstructs the AGV route and can result in an accident and further delays. ANDON systems or just signs can avoid mistakes and avoid delays.

- **Improve flexibility through human-machine automation interactions**: Human errors and biases are hard-wired and are more difficult to solve than they may seem. The company culture affects human-machine interactions, e.g., in lean cultures, people contribute to continuous improvement; however, flexible manufacturing systems are not always lean environments.
- **Adopt system thinking**: flexibility is a system property; therefore, although a company should analyse performance at the machine and department level, it is also required to implement system thinking and analyse and improve the whole system. For example, Factory 4.0 refers to a smart system which is at the same time efficient and flexible.

5.3 Limitations and future research

This study conducted a literature review which as a research method has the known limitation of depending on specific articles selected using inclusion criteria such as publication type (Zheng et al. 2020); studies published as conference papers and book chapters were excluded even though some of them could include empirical investigations relevant to this study. The literature review focused on smart and flexible manufacturing, yet other topics such as sustainability and post-covid disruption have research interests (Ghobakhloo et al., 2021).

The case study examined a single company in the UK. Future studies should conduct cross-case analysis and survey more sectors and countries to reveal how Industry 4.0 technologies impact flexible manufacturing. Further, due to the pandemic outbreak, several companies are considering reshoring their manufacturing and warehouse operations back to their homeland or nearshoring to neighbour countries; such a development can increase the use of AGVs since labour costs are typically higher in developed countries than in developing one and future research should examine the impact of AGVs in reshoring and nearshoring flexible manufacturing systems.

5.4 Conclusions

Across the globe, manufacturing systems are being disrupted by Industry 4.0 technologies such as autonomous vehicles, the Internet of things, cloud computing, and big data analytics. Further, global mega-trends, such as post-pandemic disruptions, geopolitical crises, demand shifts due to inflation, sustainability pressures, and supply shortages, redefine what we understand as flexible manufacturing systems. Companies, therefore, require (i) a better understanding of what flexible manufacturing systems constitute in the era of Industry 4.0 and (ii) a plan of how to assimilate disruptive technologies, i.e., how to design, operate, and control flexible manufacturing systems in the current uncertain business environment. This study addresses both challenges: first, a literature review provides an understanding of flexible manufacturing systems; then, an empirical study of actual AGV implementation provides insights on how to assimilate these technologies and integrate them with existing processes and personnel. Socio-technical systems theory has provided useful insights in similar investigations, but this is the first study to apply and elaborate this theory to flexible manufacturing systems. The literature review uncovers four key themes: (i) AGVs impact on warehousing management, (ii) Scheduling and routing of AGVs, (iii) Human-Machine Interface, and (iv) AGV/ IoT integration.

These themes reveal the importance of operational efficiency in flexible manufacturing systems via advanced scheduling, routing, and warehousing management. However, they also map the road for future research agenda: HumanMachine Interface in the era of smart, flexible manufacturing systems takes new forms, such as AGV robots recognising the gestures and (facial) expressions as programming commands, and employees using augmented reality and virtual reality to communicate and control with machines and autonomous vehicles. A considerable body of literature has examined the scheduling and routing of AGVs for material handling via advanced analytic methods, such as simulations, graph theory, and heuristic algorithms. Nevertheless, the advent of

IoT and technologies such as 5G and cloud and fog computing allows the real-time planning, executing, and evaluation of routing/scheduling. The integration of AGVs with IoT creates a cyber-physical system allowing applications such as digital twins that require further investigation.

This study also empirically examined the paradigmatic shift of a UK manufacturing company by assimilating AGVs and IoT to transform into a smart, flexible manufacturing system. The study finds significant improvements, including an increase in Overall Equipment Efficiency (OEE), better AGV utilisations via increased capacity and workload, reduced AGVs errors, especially in grey areas, enhanced AGV-personnel interactions which reduce AGV delays, better material handling control via real-time communication and control via IoT, and the potential to make further improvements via the full-scale installation of IoT without the need to acquire more AGVS thus avoiding any additional cost. Based on the findings, the study is able to provide specific managerial recommendations, including (i) gathering relevant data to assess technology impact for the specific company, (ii) calculating current AGV workload, (iii) analysing process delays, (iv) improve manufacturing flexibility by enhancing human-machine automation interactions, and (v) adopting system thinking to sustain flexibility as a system's property.

The study recommends that managers should broaden their views on manufacturing flexibility and get a systematic, holistic approach to the manufacturing environment; novel insights into the design, operation, and control of flexible manufacturing systems. This study contributes to the more extensive discussion of low productivity 2.0, i.e. despite the increased industrialisation and considerable investments in technology, companies and economies do not see significant increases in productivity and efficiency. That was also true with the case under investigation until the implementation of AGVs with IoT and their integration with existing employees; the socio-technical approach allows companies to manage human-machine interactions appropriately. An investment in technologies like IoT without considering their impact on people's performance could lead to technology underutilisation and reduced efficiency. It is not until the technology is appropriately managed that productivity increases. This study extends the socio-technical systems theory to flexible manufacturing. It suggests that a system's logic should guide the design, operations, and control of flexible manufacturing systems, especially in dynamic environments.

Data Availability Statement

The data supporting this study's findings are available from the second author [RM Pascazzi] upon reasonable request.

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1. Tables and Figures 7 Tables

Table 1 Routes distance and cycle time

Stations	Length [m]	CT [min]
1	544	21.76
2	516	20.64
5	436	17.44
4	451	18.04
3	514	20.56
6	210	8.4
OC - PS	280	11.2

Table 2 Example of Daily record of AGV journey's efficiency

Trip n	Total time	Blocked 1	Blocked 2	Blocked 3	Blocked 4	Break	Total time stopped	CT (wo stops)	OEE (w stops vs wo stops)	OEE (w stops vs theoretical)	Time waiting
Trip 1	00:43	00:17	00:02	00:12	00:00	00:00	00:31	00:12	28%	28%	00:00
Trip 2	00:18	00:04	00:00	00:00	00:00	00:00	00:04	00:14	78%	67%	00:00
Trip 3	00:18	00:03	00:03	00:00	00:00	00:00	00:06	00:12	67%	67%	00:00
Trip 4	00:14	00:01	00:00	00:00	00:00	00:00	00:01	00:13	93%	86%	00:00
Trip 5	00:15	00:02	00:00	00:00	00:00	00:00	00:02	00:13	87%	80%	00:00
Trip 6	00:12	00:00	00:00	00:00	00:00	00:00	00:00	00:12	100%	100%	00:00
Trip 7	00:17	00:04	00:00	00:00	00:00	00:00	00:04	00:13	76%	71%	00:00

Trip 8	00:15	00:02	00:00	00:00	00:00	00:00	00:02	00:13	87%	80%	00:00
Trip 9	00:12	00:00	00:00	00:00	00:00	00:00	00:00	00:12	100%	100%	00:00
Trip 10	00:17	00:01	00:03	00:00	00:00	00:00	00:04	00:13	76%	71%	00:00
Trip 11	00:16	00:02	00:02	00:00	00:00	00:00	00:04	00:12	75%	75%	00:00
Trip 12	00:14	00:02	00:00	00:00	00:00	00:00	00:02	00:12	86%	86%	-

Table 3 Summary of AGV journey's efficiency

Day	OEE			Total time used			Load capacity used		
	AGV 1	AGV 2	AGV 3	AGV 1	AGV 2	AGV 3	AGV 1	AGV 2	AGV 3
1	72%	91%	90%	100%	29%	46%	29%	80%	45%
2	75%	91%	85%	100%	44%	43%	22%	100%	49%
3	86%	63%	80%	100%	58%	10%	24%	100%	50%
4	68%	70%	72%	100%	70%	34%	24%	80%	67%
5	79%	85%	72%	100%	68%	55%	35%	78%	51%
6	69%	86%	73%	100%	84%	75%	33%	78%	42%
7	77%	92%	95%	100%	84%	87%	40%	69%	31%
8	73%	80%	78%	100%	63%	71%	29%	86%	43%
9	74%	83%	76%	100%	60%	55%	27%	88%	49%
10	76%	81%	81%	100%	62%	45%	24%	88%	51%
Average	75%	82%	80%	100%	62%	52%	29%	85%	48%

Table 4 Results from positioning tests

Zones	Left inf corner	Right sup corner	AGV 1	AGV 2	AGV 3

	X1	Y1	X2	Y1	No of times at zone	Time at zone	Time stopped	No of times at zone	Time at zone	Time stopped	No of times at zone	Time at zone	Time stopped
1	62	40	86	23	427	00 03:11:13	00 02:24:15	2463	00 03:52:20	00 03:09:56	0	00 00:00:00	00 00:00:00
2	63	15	84	-4	860	00 00:23:41	00 00:12:36	807	00 00:17:58	00 00:15:08	4488	00 03:57:03	00 03:22:30
3	85	24	115	-4	1248	00 03:30:28	00 02:42:33	1150	00 02:56:52	00 01:32:35	4846	00 03:27:36	00 02:06:11
4	0	0	0	0	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00
5	0	0	0	0	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00
6	0	0	0	0	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00
7	0	0	0	0	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00	0	00 00:00:00	00 00:00:00
	Min x-y speed				Total control time	00 07:22:22		Total control time	00 07:17:07		Total control time	00 07:31:21	
	2.5				Total time stopped	00 05:56:03		Total time stopped	00 05:02:13		Total time stopped	00 05:29:00	
					Start	71.47	6.35	Start	75.78	17.57	Start	82.74	3.71
					End	111.48	2.3	End	104.2	0.64	End	93.37	20.3

Table 5 AGV 1 workload calculation

Area	Output / shift - Demand	Output / shift - Max	Shift prod.	Material 1	Material 2	Material 3	Material 4	Material 5	Boxes per shift	Boxes per trolley	No. of trolleys	Trolley per AGC	Loops per shift	AGC	CT	Total time
AGV 3																
Oil Coolers	356	385	3	Steelwork					30	8	4	2	2	Charlotte	8.4	16.8
			Parts per product													
			Parts per shift	712												
			PPB -->	24												
			Total boxes -->	30	0	0	0	0								
Mods 1 - 5	180		2	Sidemembers					60	8	8	2	4	Charlotte	24	96
			Parts per product	2												
			Parts per shift	360												
			PPB -->	6												
			Total boxes -->	60	0	0	0	0								
AGV 2																
5R	240		2	Sidemembers	Tanks	Gaskets			98	6	17	3	6	Lucy	24	144

			Parts per product													
			Parts per shift	480	480	480										
			PPB -->	10	10	300										
			Total boxes -->	48	48	2	0	0								
6R	175		2	Sidemembers	Tanks	Gaskets			72	6	12	3	4	Lucy	24	96
			Parts per product													
			Parts per shift	350	350	350										
			PPB -->	10	10	300										
			Total boxes -->	35	35	2	0	0								

Area	Output / shift - Demand	Output / shift - Max	Shift prod.	Material 1	Material 2	Material 3	Material 4	Material 5	Boxes per shift	Boxes per trolley	No. of trolleys	Trolley per AGC	Loops per shift	AGC	CT	Total time
OC - Press shop	288		3	Gallery plates	Inner fins	Bottom plate			179	12	15	1	15	Emily	12	180
			Parts per product	25	22	1										
			Parts per shift	7200	6336	288										
			PPB -->	65	100	200	1000									

			Total boxes -->	111	64	2	2	0								

Table 6 Workload result

AGC	OEE	Total usage time	Workload
AGV 3	82%	292.68	68%
AGV 2	80%	141.00	33%
AGV 1	75%	128.00	30%

Table 7 IoT positioning systems

System	Location of supplier	Type of tracking	Accuracy	Tags power source	Tag battery life	Data extraction	Cost (6 AGCs)	Increase +1 cart	Annual cost	Comments
IoT1	Spain	UWB	0.5 m	Internal battery	3 years	Yes	£ 65,00	£ 115	-	
IoT2	Germany	UWB	0.5 m	2xAA battery	3 years	Yes	£ 35,000	£ 79	£ 10,000	Annual soft cost (€11.000)
IoT3	France	UWB	0.5 m	Internal battery	10s – 5 years 1 s – 1 year	Yes	€ 21,000	£ 73	£ 1000	Trial kit £ 3000
IoT4	US	UWB	1 m	Internal battery	6 days	Yes	£ 115,000	£ 192	-	
IoT5	UK	UWB Gateway	8m	-	-	Yes	£ 150,000	-	-	-
IoT6	Estonia	UWB	0.5 m	Internal battery	-	Yes	-	-	-	
IoT7	Germany	UWB	0.5 M	Internal battery	-	Yes	£ 26,000	-	-	
IoT8	Germany	BT Beacons	8 m	cr2032 battery	1 Year	Yes	£ 26,000	£ 10	£ 10,000	Annual soft cost (€11.000)
IoT9	UK	RFID - EPS WiFi	> 1m	24v (1.5W)	1 Year	Yes	£ 100,000	£ 150	-	

2. Figures

Figure 1 Caption: AGVs flowchart

Figure 1 Alt Text: A diagram that shows the routes of two Autonomous Guided Vehicles (AGVs) moving across the factory floor

Figure 2 Caption: Spaghetti chart map

Figure 2 Alt Text: A map of the factory floor showing the continuous flow line tracing the path of one AGV in real time

Figure 3 Caption: Heatmap results

Figure 3 Alt Text: a map of the factory floor that depicts in colour (red) where AGVs stop indicating possible problems in their routing which require investigation.

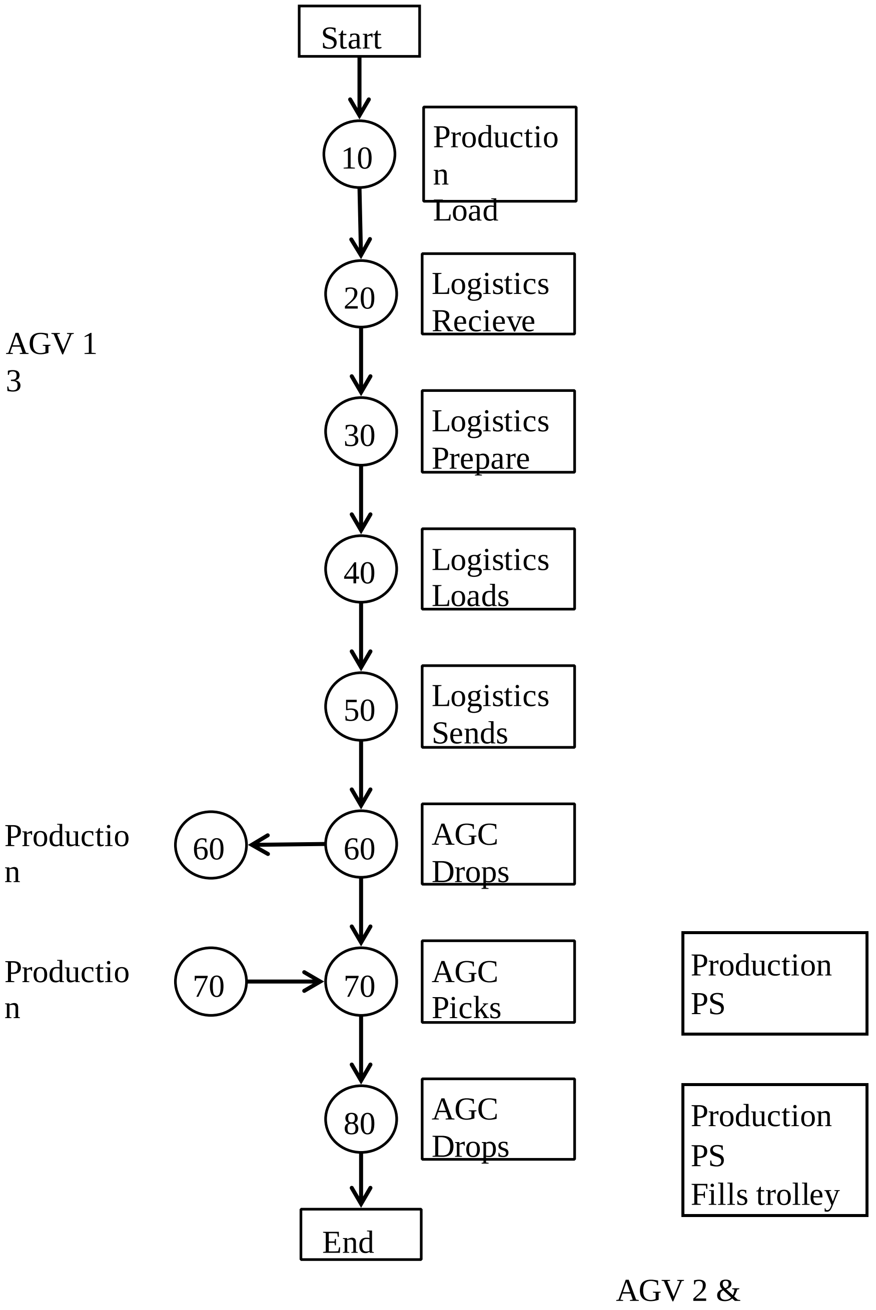
Figure 4 Caption: IoT Positioning within Alpha

Figure 4 Alt Text: A map of the factory floor showing where Internet of Things (IoT) antennas have been placed to cover the areas AGVs are operating.

Figure 5 Caption: IoT-AGV Positioning system

Figure 5 Alt Text: A map of the factory floor showing where IoTs antennas should be placed to cover the whole factory and create a cyber-physical manufacturing system

Figure 1: AGVs flowchart



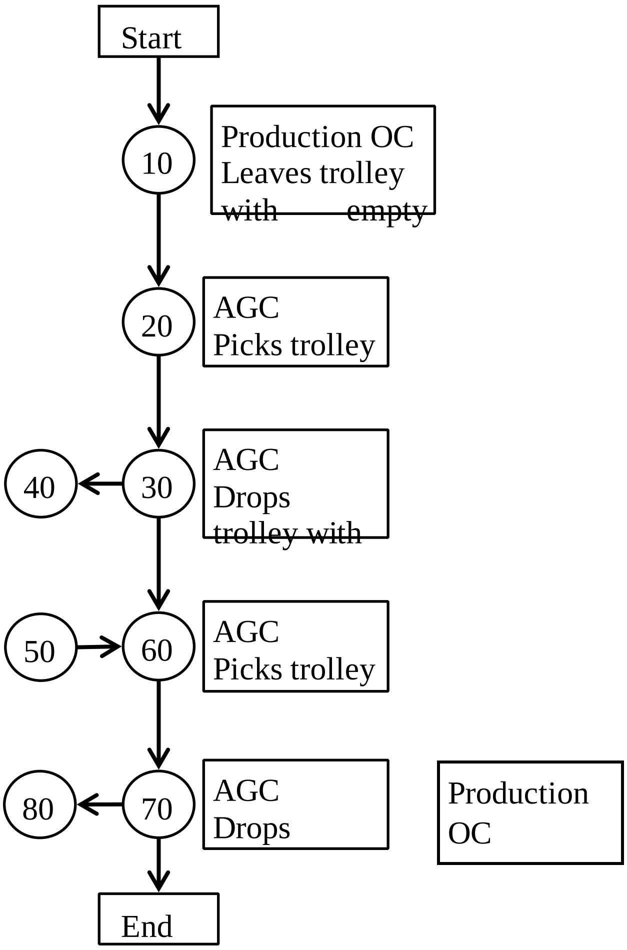

Start
10
Production OC
Leaves trolley
with empty
20
AGC
Picks trolley
40
30
AGC
Drops
trolley with
50
60
AGC
Picks trolley
80
70
AGC
Drops
Production
OC
End

Figure 2. Spaghetti chart map

Figure 3. Heatmap results

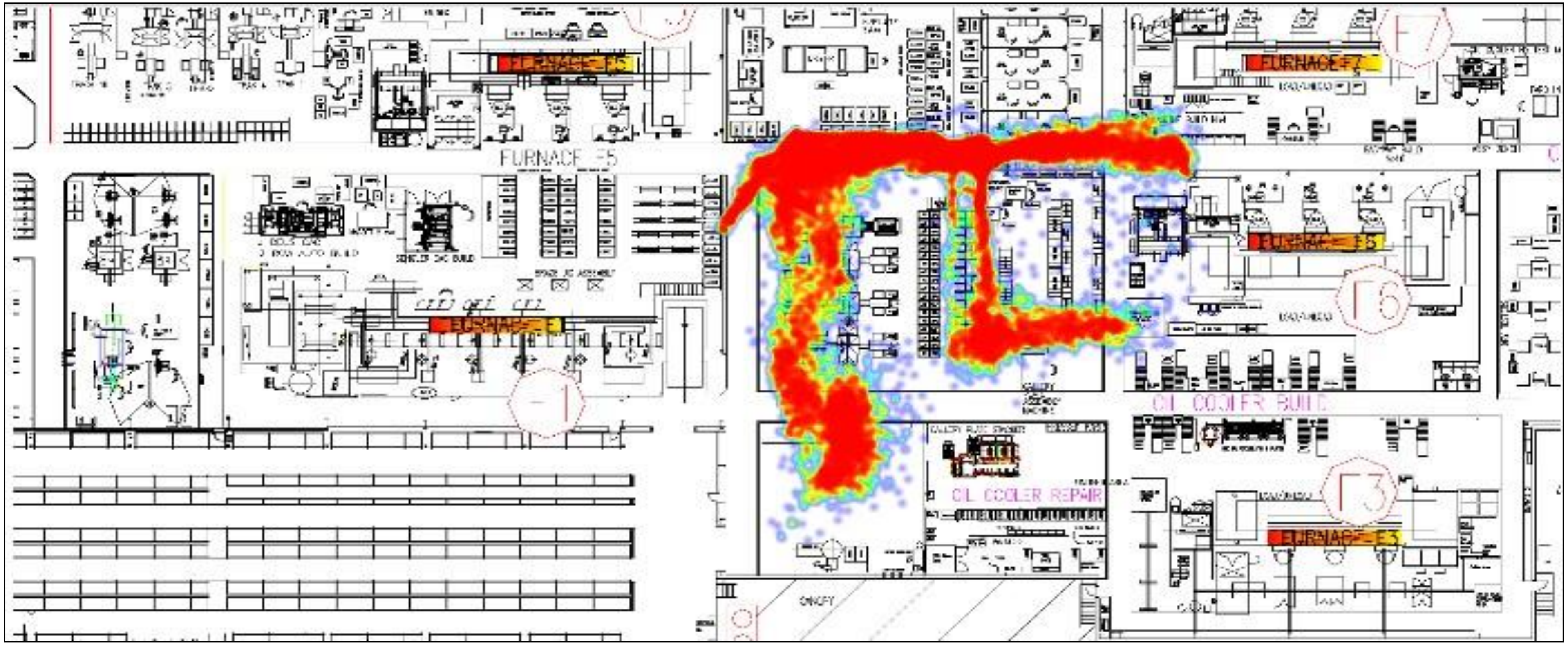


Figure 4. IoT Positioning within Alpha

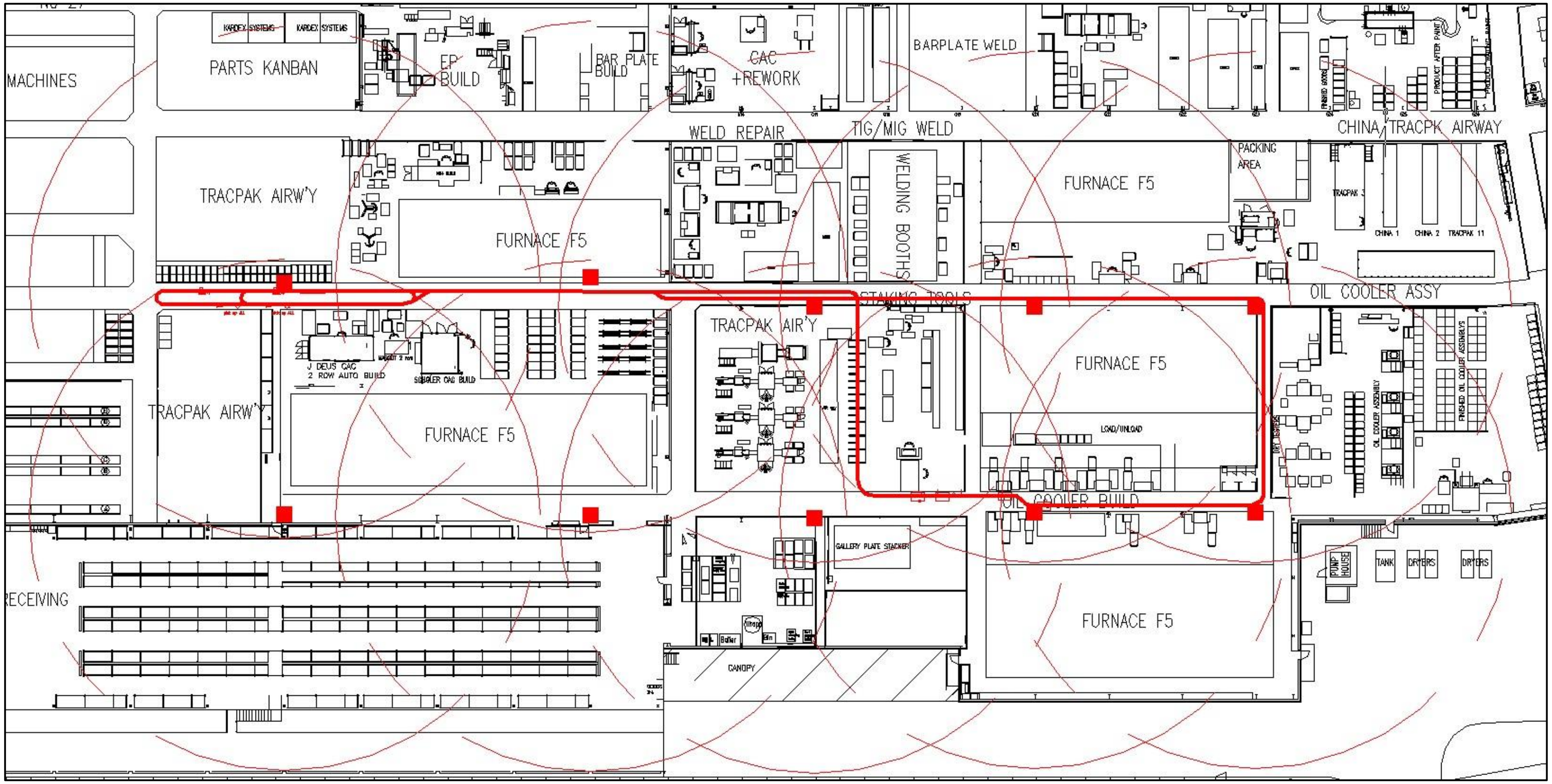
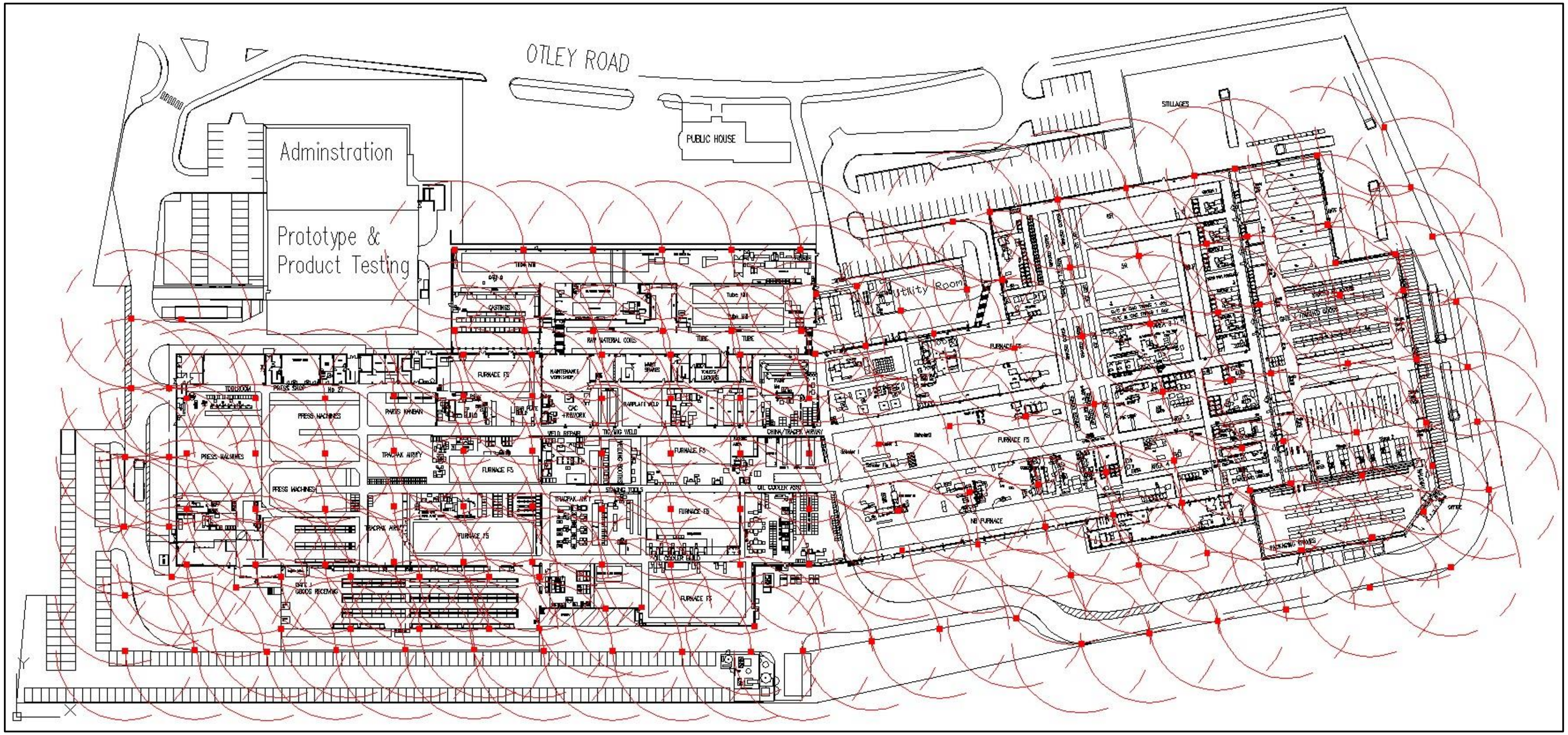


Figure 5. IoT-AGV Positioning system


OTLEY ROAD
PUBLIC HOUSE
STILLAGES
Adminstration
Prototype & Product Testing
Utility Room
CASTINGS
Tube Mill
RAW MATERIAL COILS
TUBE
TUBE
TOOLROOM
PRESS SHOP
PRESS MACHINES
PARTS KANBAN
FURNACE F5
MAINTENANCE WORKSHOP
MAINT SPARES
TOILETS/ LOCKERS
CAC +REWORK
BARPLATE WELD
WELD REPAIR
TIG/MIG WELD
CHINA/TRACPK AIRWAY
PRESS MACHINES
TRACPAK AIRWAY
FURNACE F5
WELDING BOOTHS
FURNACE F5
PRESS MACHINES
STAKING TOOLS
OIL COOLER ASSY
TRACPAK AIRWAY
TRACPAK AIRWAY
FURNACE F5
FURNACE F5
OIL COOLER BUILD
GATE 1 GOODS RECEIVING
FURNACE F5
FURNACE F5
FURNACE F5
NB FURNACE
AREA 3
AREA 4
AREA 5
GATE 3 FINISHED GOODS
PACKAGING FRAMES
OFFICE