



# WIRELESS TECHNOLOGIES FOR LEAN MANUFACTURING – A LITERATURE REVIEW

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**ABSTRACT**

The paper discusses possible applications of wireless technologies in support of lean manufacturing tools. The typology of lean tools is provided. It distinguishes three main categories, which are identification and analysis of waste, improvement implementation, and process monitoring. The set of lean tools was analyzed in terms of information requirements. On the other hand, the typology of wireless technologies was discussed including RFID and Wi-Fi. The literature review of wireless technology applications for support of lean tools was conducted. The literature was systematically reviewed from the point of view of specific technologies and specific tools which were the subjects of the analyzed publications. Both typologies were synthesized to establish a framework for wireless technologies applications in the context of lean manufacturing implementation. It also could serve as a guideline for lean practitioners and implies future research directions. This paper is an extended version of paper published by [1].

**KEYWORDS**

lean manufacturing, Toyota Production System, wireless technology, RFID, Radio Frequency Identification.

## Introduction

Currently, technology may permit more complex and flexible manufacturing processes than was possible in the past. New technologies, like bar-coding, RFID (Radio Frequency Identification) and mobile devices, give a new opportunity to aid in the deployment of the Toyota Production System (TPS) that formed the basis for lean manufacturing, long before those technologies were brought to the shop-floor [2]. New technologies' time to market is decreasing significantly. It is hard to imagine offices without mobile phones and wireless (Wi-Fi) networks. There is visible effort in excelling wireless technologies (WTs). Starting from smartphones as devices for wireless connection with relatives and co-workers (calls, e-mails, social networks, messaging, documents etc.), through lower level technologies like wireless pow-

er charging, near field communication (NFC), Bluetooth and many others. WTs also offer a wide spectrum of applications on shop-floor and industrial level. There are many case studies of implementations of such technologies. On the one hand they offer potential for significant improvement or even process innovations in many cases. On the other hand, they entail costs of investment, exploitation, maintenance, but also a new kind of waste and risk for companies (e.g. social networks and viruses).

Lean manufacturing is a well-established philosophy of improving enterprise processes. WTs could be applied to lean organization and reduce waste. There is extensive evidence that WTs can be successfully combined with lean techniques and principles in a wide variety of organizations [3–5]. The spectrum of lean techniques and wireless technologies is broad. Therefore, the question arises which technique could

be supported by which technology. The main goal of this article is to present evidence from literature on how different WTs support different lean techniques, which can be a basis for further development of the wireless lean reference model (W-Lean).

## Materials and methods

The systematic literature review strategy proposed by [6] i.e. choose, know, understand, apply, examine, combine and evaluate was adopted. In this paper studies related to lean manufacturing, wireless technologies and wireless technologies combined with lean manufacturing (see Fig. 1) were reviewed.

The ABI/INFORM, ACM, Compendex, DOAJ, EBSCO, Emerald, IEEE/IEE Electronic Library, JCR, Knovel, ProQuest, SCImago, SCOPUS, Springer, Taylor and Francis, Wiley, WoS databases were chosen for the review. The initial searching query is presented in Fig. 2.

In the next step, the phrases 'lean thinking /manufacturing/management/production' were replaced with the names of popular lean tools, techniques and concepts (abbreviations and full names) i.e.:

- 5S,
- Andon,
- flow management,
- Kanban,
- Heijunka,
- JiT, Just in Time,
- milk run,
- poka-yoke (error proofing),
- SMED, Single Minute Exchange of Dye,
- SPC, Statistical Process Control,
- SQC, Statistical Quality Control,
- supermarket,
- TPM, Total Productive Maintenance,
- visual management,
- VSM, Value Stream Mapping.

We included documents that discussed applications of wireless technologies and lean principles and/or tools in manufacturing and logistics. We excluded documents that were not in English, papers on applications of lean management in fields other than manufacturing and logistics i.e. lean healthcare or lean administration [7, 8]. Papers dated 2008–2017 were investigated. We also reviewed reference lists of found articles for important references missed in the database search.

35 relevant works (see Appendix A) were selected after screening abstracts of found papers.

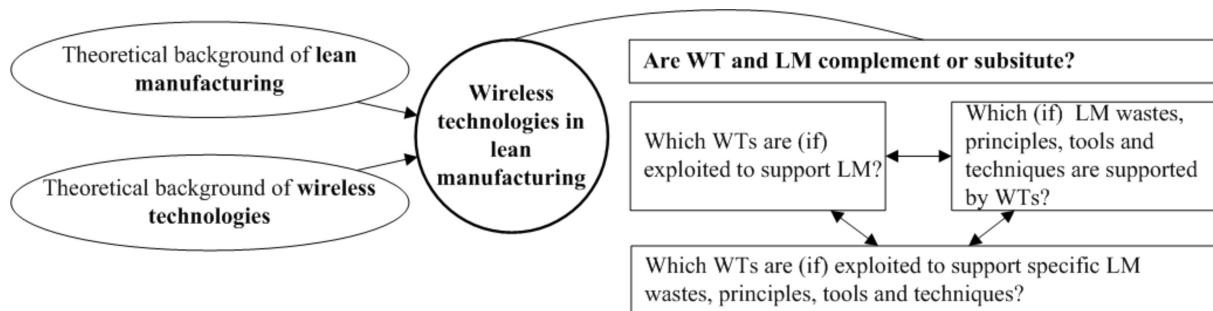


Fig. 1. Framework of the study.

```
[ 'lean'
AND
( 'manufacturing' OR 'production' OR 'management' OR 'thinking' OR 'techniques' OR 'tools' ) ]
AND
( 'wireless' OR 'RFID' OR 'RTLS' OR 'Industry 4.0' )
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Fig. 2. Initial query.

## Lean manufacturing

The lean manufacturing concept focuses on the identification and elimination all types of waste occurring in the production processes. Ohno [9], the author and designer of the Toyota Production System, defined 7 types of waste:

- transportation,
- inventory,
- motion,
- waiting,
- overproduction,
- over-processing, and
- defects.

It should be stressed that the same types of waste can be observed not only in production processes but other areas as well e.g. administration, healthcare.

In practice, a specific waste usually influences other types of waste. So, when improvements in the process focused on waste elimination are planned, their influence on all types of waste should also be taken into account. Especially in the case of overproduction – this type of waste usually generates inventory and other types of waste in succeeding operations. All lean methods and techniques focus on identification and elimination of all the types of waste mentioned above.

The Lean Manufacturing concept became very popular after the publication of the research results obtained by several MIT research teams. They analyzed, among others, the sources of Japanese carmakers' competitive advantage over American ones. The research program in particular focused on analysis and comparison of production systems. This research resulted in publications by [10], who investigated organization of assembly process and famous books [11, 12], which described the following lean rules:

- value,
- value stream,
- flow,
- pull,
- perfection.

All activities should be focused on the creation of value defined by the customer. In case of the internal processes it could be customer of the process. Usually in the manufacturing processes appear value added, required but non-value added, and non-value added (waste) activities. The value is provided through processes. All processes should be mapped and analyzed in the context of value generated by the process. All processes should be performed without stoppages and backflows. Process should perform according to the customer tact time. All processes should be performed in just in time manner. All ac-

tivities should be performed in a perfect way. When any problem occurs, it should be solved immediately.

Later publications placed particular emphasis on people [13]. Due to this, later publications on lean management include an additional rule – Respect People [14].

All the methods can be divided into 3 categories:

- identification and analysis of waste e.g. causal diagrams, Value Stream Mapping (VSM);
- improvements implementation e.g. Single Minute Exchange of Die (SMED), poka-yoke;
- process monitoring e.g. andon, supermarket.

It should be stressed that often the same methods or tools have different purposes. Not all methods and tools, especially for improvements implementation and process monitoring are utilized only in the Lean concept. Usually they are also utilized in other approaches focused on production process improvement.

## Wireless technologies

There have been many attempts to define information and communications technology (ICT) [15]. ICT is an extended term for information technology (IT), which underlines the role of communications (and telecommunications). ICTs are 'technologies used by people and organizations for their information processing and communication purposes' [16]. Even though in the literal sense ICT includes IT, it is practically used in the same meaning by most practitioners. This article adopts this point of view.

Wireless technology (WT) is a very broad term. WT is defined as an ICT used to transfer information and enabling communication between people and/or machines, as well as identification of objects, with no wires. WTs form a substantial part of a broader ICTs group, especially in developed countries. WTs are widely used by companies and individuals (e.g. communication with friends, social networks, mobile apps). They have evolved dramatically in the last decade. This concerns technologies and standards for wireless communication, wireless networks, wireless sensors, remote identification e.g.:

- Bluetooth,
- GPS, GLONASS,
- LTE,
- Radio Frequency Identification (RFID),
- Wi-Fi, among others.

WTs applicability was surveyed for many branches e.g.:

- healthcare [17],
- home and building automation [18],

- public safety [19],
- agriculture [20].

It is also of interest for industrial, manufacturing, logistics and service companies [21, 22].

Most people understand the term WTs to cover technologies exploiting radio waves. It should be mentioned that there are also other possibilities to transfer data with no wires e.g.:

- optical technologies like bar codes or light fidelity (Li-Fi), and
- sonic (especially ultrasonic) technologies.

Maurino and Sirico [3] divided WTs into two groups i.e. tactical wireless, related to technologies invisible for end-users, so-called shop-floor technologies, and wireless communication including e.g. Wi-Fi-enabled mobile devices and Internet/Intranet applications. The most popular tactical wireless in companies is RFID. There is no widely adopted definition of RFID. In this paper this term is taken to mean any technology that enables identification of a tagged object via radio waves (regardless of the frequencies, standards etc.). There is no classification of RFID systems, but some attempts were made. Typology of RFID systems considering frequencies, reading rules, use cases and forms of devices was proposed by [23] (see Appendices 1–2) and [24].

Huang, Wright, and Newman [21], when discussing wireless manufacturing (WM) concluded that it is ‘an umbrella for a suite of RFID solutions for manufacturing applications’ and ‘WM relies substantially on wireless devices such as RFID or Auto ID sensors and wireless information and communication networks such as Wi-Fi and Bluetooth for the collection and synchronization of the real-time field data from manufacturing workshops’. Therefore, this conclusion is in line with the division into tactical wireless and wireless communication [3].

A classification of wireless communication technologies was proposed by [25]. However, it is limited to applicability for intelligent transport systems and is outdated. It includes the following classes:

- Bluetooth designed for voice and data transmission over small distance (~10 m) between devices, characterized by low power consumption, low cost, low complexity, robustness (2.4 GHz),
- Cellular networks (e.g. GPRS) designed mainly for voice data exchange (GSM/GPRS/EDGE: 0.8–1.9 GHz),
- Communication Air-Interface for Long and Medium-range communication (CALM) for direct vehicle to vehicle communication (5–6 GHz),
- Worldwide Interoperability for Microwave Access (WiMAX), based on the IEEE 802.16 standard (2–66 GHz) designed to provide wireless data over long distance,
- Dedicated Short-Range Communication (DSRC)/Wireless Access in the Vehicular Environment (WAVE) built on IEEE 802.11p for roadside equipment to collect data and propagate data from/to vehicles (5.8–5.9 GHz),
- Digital Video Broadcasting/Digital Audio Broadcasting (DVB/DAB) family of technologies (6–8 MHz) designed for global delivery of digital multimedia and audio services,
- Millimeter-wave (MMWAVE) designed for short-range applications with high data rates (60–64 GHz),
- Infrared (IR) suitable for applications requiring lane-specific communication (2.6 GHz),
- Wireless local area network (WLAN) supporting IEEE 802.11 set of standards (2.4–5.2 GHz), designed for high data rates and reliability, a.k.a. Wi-Fi,
- ZigBee supporting IEEE 802.15.4 standard designed (2.4–2.5 GHz) for data transmission for sensor-based application.

Above list lacks important technologies which are:

- CDMA one (IS-95) and CDMA2000 (IS-2000) which are currently the most popular 2nd and 3rd generation mobile telecommunication in North America and South Korea,
- DASH7 standard for wireless sensors and actuators, originated from ISO18000-7 for 433 MHz band, but actually covering all sub-GHz industrial, scientific, medical (ISM) bands,
- Li-Fi (Light Fidelity), which is an emerging optical wireless communication [26], that is of interest of many researches currently and some foresee it will supplement or even supplant Wi-Fi networks [27],
- LTE (Long Term Evolution) which is 4th generation standard for cellular networks and is preferred over WiMAX by telecom companies (700/800/900/1700/1800/1900/2100/2600/3400/3600 MHz),
- UMTS (Universal Mobile Telecommunications System) which is currently the most popular 3rd generation mobile telecommunication in Europe, Japan and China,
- 5G (fifth generation of cellular mobile networks).

Wireless technologies offer almost unlimited possibilities of business application, from pure identification with passive RFID, through wireless sensor networks and real time locating systems (RTLS), to mobile communication and applications almost everywhere. Therefore, it seems also prospective to sup-

port lean manufacturing. The next section presents ways in which WTs can support lean manufacturing based on examples of various lean improvement techniques and tools, lean principles and wastes.

## Wireless technologies for lean manufacturing

### Background

As lean and ICT became well established, researchers and practitioners noticed that there is a question of their coexistence. ICT could be useful for leaning certain tasks, but also could be a source of wastes and inefficiencies [28]. Nicoletti [29] proposed and verified a framework for an integrated approach to process improvement including lean and ICT. Bell and Orzen [30] wrote probably the first definitive and comprehensive book on ‘lean IT’, discussing two primary dimensions. Outward-facing lean IT engages IT to achieve lean principles (IT for lean). Inward-facing lean IT improves the position of IT organizations with lean principles (lean for IT). A case study of lean applications for software development and ICT hardware providers was presented by [31]. In some cases, ‘IT investment is one of the minimum requirements of Lean Manufacturing System implementation (...)’, as IT investments can offer competent administrative advanced manufacturing technologies to effectively manage all production processes [32]. Huang, Wright, and Newman [21] study contains a review of case studies of WTs implementation in manufacturing companies. It shows the spectrum of possible applications, but is not focused on matching specific WTs with specific lean tools and techniques. It directly addresses only the Just in Time (RFID-enabled Kanbans) and Total Productive Maintenance concepts. The study could be updated due to rapid development of WTs. Considering WTs as a sub-group of ICTs, there are two dimensions of WTs and lean integration (by analogy to [30]) i.e.:

- outward-facing lean WT (WT for lean) and
- inward-facing lean WT (lean for WT).

Kolberg, Knobloch, and Zühlke [33] presented use cases of a smart operator, smart machine, smart product and smart planner discussing combination of lean manufacturing and Industry 4.0. This article is focused on WT for lean and the question of how lean manufacturing could be supported/improved with WT. Applications of lean thinking in design, deployment, management of WT-related projects, programs, organizations are out of the scope of this pa-

per. However, there are also many examples of such lean WT integration e.g. [31]. An example of parallel applications of both lean for WT and WT for lean was given by [34], where wireless devices support poka-yoke, which is used for lean information system design. Another important element is awareness of the existing waste in WT systems. Three types of problems occur [3] i.e. replicating data stored in multiple places, improper application of tools, risk associated with improperly secured wireless transmissions.

### Wastes and lean principles

The only comprehensive book found that is dedicated to the ‘wireless lean’ is ‘Thin Air’ [3]. The book describes in detail paradigms, rules and many case studies of both outward- and inward-facing lean WT. Powell and Skjelstad [35] presented conceptual framework and 2 case studies for the role of RFID in the development of extended lean enterprise by linking RFID with 5 lean principles. Neither paper [3, 35] shows clear relations between specific wireless technologies and specific lean tools. Kolberg, Knobloch, and Zühlke [33] approached integration of the Industry 4.0 concept and lean production by showing an interface framework and examples of Kanban, Andon, Heijunka and bin. It was proved that RFID helps to eliminate 7 wastes [36-38]. Rafique et al. [39] evidenced how RFID positively impacts barriers affecting lean manufacturing by conducting a comprehensive literature review on barriers in lean and RFID-based lean manufacturing. This study analyzes a set of papers related to RFID-based lean manufacturing. Simulated RFID scenarios are useful for elimination of wastes addressed in lean manufacturing [40]. Similar conclusions from two case studies of multi-national FMCG companies, where an analytical toolset for RFID opportunity analysis was also introduced were presented by [41]. The toolset addresses improvement opportunities, i.e. automatic collection of process data, timely conformance of data dependencies for processes, and increasing process visibility. Opportunities are related to wastes and those are addressed by different tools. Patti and Narsing [42] examined the question of whether RFID and lean are competitive/contradictory or compatible and concluded that in some cases RFID could eliminate wastes uncovered by lean techniques. The study was focused on the relation between RFID and different kinds of wastes in a company. However, that work also lacks systemized relations between RFID technologies and lean tools/techniques.

### Lean tools, techniques and concepts

The rest of the papers analyzed (see Appendix A) were dedicated to case studies and literature on particular lean techniques/tools and their possible support with wireless technologies, especially RFID. Frequency of occurrence of papers related to specific lean tools, techniques, concepts is shown in Fig. 3.

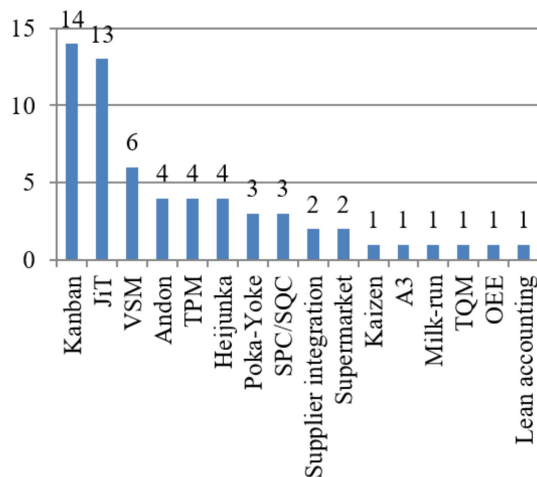


Fig. 3. Frequency of occurrence of specific lean tools, techniques and concepts.

There were 14 papers found discussing Kanbans and wireless technologies. 13 papers discussed JiT and wireless technologies. Among those two groups, six papers discussed both JiT rules and Kanbans in relation to possible wireless technologies implementations.

Rafique et al. [39] conducted a systematic literature review to justify the impact of RFID technology on handling barriers affecting implementation of lean manufacturing. The authors indicated that RFID-based solutions offer operational visibility, inventory control, production control, minimized lead times and the real-time data information (to facilitate top management and employees on shop floor), therefore enable just in time concept implementation. They mentioned RFID-based Kanbans discussed by [43] as one of the possible solutions, where author presented integrated application of RFID-based lean manufacturing by development of RFID-based Kanban management systems as the tool for achieving just in time concept. Lage Junior and Godinho Filho [44] presented review of variations of Kanban systems including electronic Kanbans, where physical signals are replaced by electronic signals. Their analysis is limited just to benefits of electronic signals with very limited discussion of wireless technologies (especially RFID) as a mean to implement electronic Kanbans in manufacturing. Reference [45] addressed Kanban

system as the essential part of just in time and discussed principles and planning process of electronic Kanban system.

They explained how RFID tags can be used to report the material batch status, number of batches, its locations and how wireless technologies can be used to report different actions or changes in production batch status enabling calculation of schedules and update of Kanban parameters based on the real time data. Chongwatpol and Sharda [40] prepared discrete-event simulation of 1-dimensional barcode, 2-dimensional barcode and RFID technology in real job-shop environment. The results showed that employing RFID in lean manufacturing can reduce most wastes, but overproduction was increased in their study. They concluded that increase of visibility through RFID should be analyzed by companies as a possible solution to enhance lean initiatives. Barbosa et al. [46] discussed application of wireless communication via tablets to enable real time pull signaling when there is an issue of long distances between units on site.

Several other authors suggested, conceptualized and evidenced how RFID and RTLS technology can support the Kanban system and just in time concept by providing real time data on quantity and location of objects within facility.

References [3, 33, 35, 42, 47–50] reported on an industrial case from the automotive industry where a wide variety of RFID-based shop-floor solutions was illustrated. This case illustrated that RFID-based shop-floor solutions enable just in time concept not only in large companies, but also in SMEs. Haddud, Dugger, and Lee [38] addressed the question of relation between RFID and lean manufacturing. Specifically, questions addressed the use of RFID in manufacturing control, asset tracking, and asset maintenance. They surveyed 7 U.S. manufacturing industries. Their research proved that it has real impact on reduction of overproduction, waiting time, inefficient transportation, inappropriate processing, unnecessary inventory, unnecessary motion, and rejects and defects, especially by enabling automated just in time strategies. Zelbst et al. [51] addressed JiT and TQM presenting real-time information sharing based on RFID technology that was proved to have positive impact on JiT and TQM programs.

Several other authors also reported on RFID potential for enabling and excelling just in time strategies by real time visibility and traceability showing case studies, concepts and simulations [48, 52–54].

There were 6 papers found discussing VSM. Chen, Cheng, and Huang [55] analyzed case study of three-tier supply chain improvement based on lean

techniques. Authors showed possible support of Value Stream Mapping used to analyze present state and future state of the supply chain, in which RFID technology is implemented. They focused on decrease of times possible due to RFID application and implementation and VSM is used as an analytic tool to support RFID implementation. A very similar case study but applied within a single warehouse instead of a supply chain was discussed by [56], where VSM was also used as an analytic tool to support RFID implementation. Ramadan, Zelong Wang, and Noche [36] proposed a system for dynamic value stream mapping based on RFID implementation. This is an example how RFID technology can support lean initiatives. Authors proposed a tool which enables drawing VSM on a basis of automated radio identification of objects flowing through a facility. This solution was later extended to support lean accounting thanks for the ability of real time cost tracking based on automated radio frequency identification [37]. Such a system enables 'identifying the root causes of redundant costs and pinpointing the costliest root causes and their locations so that their elimination becomes a top priority'. References [47, 50] discussed a similar solution (on-line) RFID-based facility performance monitoring system). VSM is created automatically in real time based on RFID tracking system. Real time generation of VSM has several benefits such as time saving, errors reduction, enhancing visibility to the managers, enabling more accurate lean initiatives addressing problems identified through real time VSM.

Wireless andons are basically about simplification of installation of Andon signs, as communication is performed wirelessly [3, 33, 57, 58]. It also enables higher flexibility of installed devices and easy reconfiguration of the solution if needed. Wireless Andons are already widely available on the market.

Several publications presented examples of implementation of digitized Heijunka boards, usually as a support of Kanban implementation [3]. These examples relate to mechatronic industry [33], automotive industry [59] and construction industry, on area of 55 hectares [46]. IT technology gives a possibility extend area of operation such tool, not only limited to the one plant.

There were four works found discussing TPM [3, 48, 58, 60]. Santos et al. [58] additionally addressed the OEE factor directly. Data gathered from machines could be communicated wirelessly, enabling easy, fast and real-time computations of the OEE factor, as well as real-time diagnosis as part of TPM initiatives [58]. There is an example of RFID application for real-time monitoring of critical equipment

– turbine [60]. Another example of RFID utilization for maintenance and installation instructions in manufacturing processes as well as for the maintenance process monitoring [48].

In this paragraph tools that were identified 3 or fewer times are discussed i.e. poka yoke, SPC/SQC, supplier integration, supermarket, kaizen, A3 and milk run. Three works discussed wireless technologies applied for poka-yoke. One application is enabling wireless communication for pick-by-light solutions [61]. The second one is wireless devices used for real time data entry into information systems, therefore enabling error-proofing thanks to access and decision making based on actual data [34]. Kolberg, Knobloch, and Zühlke [33] discussed error-proofing idea of automated notification when tact time is exceeded based on RFID-based Kanban system and indicates the great opportunity of introducing error-proofed interfaces when digitizing lean tools and introducing software applications. The literature discusses a number of implementation of SPC/SQC systems. Li, Zhang, and Li [62] presented an example of setting times in RFID tags for real-time quality control of production line performance. Shih and Wang [63] described an application of wireless sensor system for real-time monitoring of temperature for 'cold chain' in food industry. RFID-based system could be also support data mining system for quality improvement in the operational processes in garment industry [64]. Wireless technologies support operation of kanban system which connects the company with an external supplier, therefore enabling supplier integration [3]. The literature presented an example from a logistics company [54]. Supermarket, as a support for electronic Kanbans for an automotive supplier company, was presented by [33]. The RFID technology helps to calibrate the supermarket size [59]. There are also some examples for supporting Kaizen initiatives by wireless technologies [3]. Wireless technologies could also support the process of management and improvement of production processes. The literature described an example of new product implementation in the airplane industry [3]. Wireless technology supports the logistic processes. Active RFID could realize several functions: identification the objects' location and sharing information about this location in real-time. Based on this information, it could be possible to design effective (based on quantitative data) logistic processes (internal and external), e.g. milk-run [65].

### **Descriptive statistics**

Appendix 3 presents the list of the papers analyzed, their topics and focus area. It is specifying

Table 1  
 Statistics of analysed papers.

	Details of WT	Set of LM principles	Set of LM wastes	Specific LM tools/techniques/concepts										
				0	1	2	3 and more	IA	II	PM	IA, II & PM	IA & II	IA & PM	II & PM
Number	8	5	7	1	17	13	4	16	22	30	10	10	14	20
Percentage	23%	14%	20%	3%	49%	37%	11%	46%	63%	86%	29%	29%	40%	57%
Legend	IA – identification and analysis of waste II – improvements implementation LM – lean manufacturing							PM – process monitoring WT – wireless technology						

what technologies were discussed. Next, it is shown if a paper relates to general assumptions of lean i.e. lean principles and wastes. Then, in the five most-right columns, lean tools, techniques and concepts addressed in papers are listed. Table 1 presents descriptive statistics.

Only few papers discussed details of WT (23%). The number of works discussing relations of WTs and elimination of the set of lean wastes (20%) was also relatively low.

Even less papers discussing how WTs support the set of lean principles (14%) were analyzed. Vast majority of papers covered the topic of lean tools and techniques only partially. 86% of papers were discussion of case studies of an application of WT to support one or two lean tools and/or techniques. It is worth to notice, that 86% of all papers addressed process monitoring.

## Discussion

- Which (if) LM wastes, principles, tools and techniques are supported by WTs?
- Which WTs are (if) exploited to support LM?
- Which WTs are (if) exploited to support specific LM wastes, principles, tools and techniques?

It was evidenced that WTs could be applied to support the full portfolio of considered wastes, principles and techniques. However, the justification of such application is a wider problem. It needs further and more detailed analysis of effectiveness including economic effectiveness of investment and exploitation of specific WT as a final estimation.

Usually in the publications specific lean methods/tools are presented in relation to the specific technology or wireless technology in general without detailing standards.

Less often the publications relate to the sets of lean principles and lean wastes. WTs are the most often utilized for process monitoring. Processes operating in a lean manner have special expectations from the information flow management.

Lean tools and concepts most frequently supported by WTs are kanbans and just in time. Heijunka and supermarket usually support the kanban and JiT implementation.

There is lack of publications depicting both details of applied WT (standards, specifications, etc.) and details of lean implementation, improved processes, eliminated wastes, organizational issues, etc.

- Are WT and LM complement or substitute?

It is clear that there is a research gap in the holistic approach to the topic of applications of WTs as a support for lean tools. WTs can have both positive and negative implications (can generate waste, e.g. redundant information).

It has been indicated that WT have a practical impact for the utilization of lean methods and tools. It was evidenced that WTs may support implementation of lean manufacturing.

The results of the research show that there exists a need for a reference model. The model should have theoretical and practical implications. In particular, it could serve as a support tool for managers. This model should consider the needs and expectations of different industries as well as different functions in the particular organization.

Future research will be focused on analysis of how particular lean methods and tools could be supported by WT. It gives an ability to create comprehensive approach useful for both WT implementation and lean initiatives.



## Appendix 1. Types of RFID systems according to reading rules based on [23]

System' types		Description		Main frequencies & standards	Typical applications	Reading range
According to a reading rule	active	tags transmit independently on reader, with own battery		433 MHz, 2.45 GHz, 5.0 GHz, 5.8 GHz see below for standards	– RTLS – long distances – sensors	up to 1000 m
	passive	tags transmit signal when interrogated by reader	without battery	LF, HF, UHF see below for standards	– logistics – access control – registering working time	0.1–10 m
	battery assisted passive BAP	with own battery to power e.g. sensors	– logistics – long distances			over 30 m
According to frequencies	Low Frequency LF	passive, BAP, LF does not allow to read/write of many tags at the same times		125-134 kHz – ISO 11784 – ISO 11785 – ISO 14223 – ISO/IEC 18000-2 – ISO/IEC TR 18047-2 – Unique	– access control – tickets – working time registration – animals' identification	up to 0.5 m
	High Frequency HF	passive, BAP read/write of many tags simultaneously		13.56 MHz – ISO/IEC 14443 – ISO/IEC 15693 – ISO/IEC 18000-3 – ISO/IEC TR 18047-3 – NFC Forum – Mifare (Ultralight, Ultralight C, Classic 1K/4K, Plus, DESFire) – I-Code (ILT, SLIX)	– access control – tickets – registering working time – libraries – automatics	up to 0.6 m
	Ultra-High Frequency UHF	active, possible communication of tags (meshing)		433 MHz – DASH7 – ISO/IEC 18000-7	– RTLS – sensors – military	up to 1000 m outdoor
		passive, BAP, longest read range of all passive frequencies, reading many tags simultaneously		860-960 MHz – ISO/IEC 18000-6 – ISO/IEC TR 18047-6 – EPC Gen2v2	– supply chain – warehousing – work in process – inventory – pRTLS accuracy up to 1 m	up to 15 m, BAP over 30 m
		active, possibility of Wi-Fi compatibility		2.4 GHz, 2.45 GHz – IEEE 802.11b/c/d/e/f/g/h/i/j – ISO/IEC 8802-11 – ISO/IEC 18000-4 – ISO/IEC TR 18047-4 – ISO/IEC 24730-2, -5 – ISO/IEC 24769 – ISO/IEC 24770	– RTLS accuracy up to 1 m – assets & personnel tracking & identification in hospitals and mines – sensors	up to 200 m
	Ultra-Wide Band UWB	active, multi bands		multiple bands simultaneously (3.1-10.6 GHz) – ISO/IEC 24730-6 – ISO/IEC 24769-6 – ISO/IEC 24770-6 – IEEE 802.15.4	– RTLS accuracy up to 15 cm – sensors	up to 300 m
Super High Frequency SHF	active, smaller and more effective than 433 MHz and 2.45 GHz, longer battery lifecycle		5.0 GHz, 5.8 GHz – IEEE 802.11a/p – ISO/IEC 8802-11 – ISO/IEC 18000-5 (withdrawn) – ISO/IEC TR 18047-5 (withdrawn)	– RTLS – sensors	up to 200 m	

## Appendix 2. Types of RFID systems according to use cases and tag's form based on [23]

	Systems' types	Description
According to use cases	Mobile reader	Pure identification with mobile readers (PDAs) and mobile applications
	Chokepoint detection	Presence detection / pure identification Mostly passive systems, frequencies dependent on environment and expected reading distances
	Door discrimination	Portals, dock doors Usually supporting algorithm and technologies needed to recognize movement direction
	Conveyor belts	Chokepoints integrated with conveyors
	Intelligent shelves	Detection with regard to particular shelf e.g. within warehouse
	Staging areas	Detection of presence within defined area on floor
	Real time locating systems	RTLS, active (mostly Wi-Fi or UWB based) or passive (pRTLS) Approximation of position coordinates (usually 2D)
	Desktop	Pure identification e.g. for encoding purposes
	Printers and applicators	Encoding RFID labels and printing additional data on it Possibly integrated in manufacturing lines, conveyor belts, labels' applicators
Dispensers and kiosks	Encoding tags and automated release of tags e.g. when tag is inserted into kiosk files are printed for the user or self-check kiosks in libraries Readers integrated into kiosks, integrated with printers etc.	
According to tags form	Cards	Used for access control, ticketing, banking, loyalty programs etc.
	Display tags	Devices with integrated RFID tags, could be used e.g. as electronic Kanbans
	Hard tags	Tags in industrial forms, dedicated for industrial and harsh environment
	Inlays	The simplest form, transparent sticker with chip and antenna
	Keyfobs	Similar application as for cards
	Labels	Printable labels with RFID inlays
	High memory tags	Tags used when no reliable access to database can be ensured
	High temperature tags	Designed to withstand high temperature e.g. ceramic tags or laundry tags, some of them withstands even 350°C
	On-metal tags	Designed to be attached to metal base
	Seals	Seals with RFID could be automatically identified and checked
	Sensor tags	Integrated with sensors of temperature, humidity etc.
Wristbands	Used for access control, patient identification etc.	

### Appendix 3. List of papers and statistics

Reference	Main topic (authors' perspective)	Related WT	Directly addressing lean						
			set of prin- ciples	set of wastes	tools/ techniques/concepts				
					Num- ber	Name	Purpose		
IA	II	PM							
Brintrup, Ranasinghe, and McFarlane (2010)	An analytical toolset to identify where RFID can bring value, eliminate wastes	-RFID i.g.	-	+	0	-none	-	-	-
Chen, Cheng, and Huang (2013)	The case study of lean and RFID implementation in lean supply chain management	-pRFID -RFID UHF	-	-	1	-VSM	+	-	-
Chen et al. (2013)	The case study of lean and RFID implementation for warehouse management. VSM used to prove RFID efficiency (lean for WT)	-pRFID -RFID UHF -EPC	-	-	1	-VSM	+	-	-
Helo et al. (2014)	MES including Andon	-WC i.g.	-	-	1	-Andon	-	-	+
Soundararajan and Jackson (2011)	Poka-yoke by wireless pick-by-light	-N.s.	-	-	1	-Poka-Yoke	-	+	-
Zhang (2010)	Poka-yoke in information system design using wireless devices	-WC i.g.	-	-	1	-Poka-Yoke	-	+	-
Dai et al. (2012)	RFID-based manufacturing execution system improving shop-floor visibility	-RFID i.g.	-	-	1	-JiT	-	-	+
Haddud, Dugger and Lee (2015)	RFID to handle 7 wastes	-RFID i.g.	-	+	1	-JiT	-	+	+
Xiu-Xu and Lin-Yan (2009)	RFID-based lean manufacturing for inventory control	-RFID i.g.	-	-	1	-JiT	+	+	+
Huang, Zhang, and Yang (2010)	RFID-based JiT system – case study	-RFID i.g.	-	-	1	-JiT	+	+	+
Patti and Narsing (2008)	Lean and RFID: friend or foes?	-RFID i.g. -aRFID -RTLS	+/-	-	1	-Kanban	-	-	+
Qu et al. (2017)	System dynamics analysis for an Internet-of-Things-enabled production logistics system	-RFID i.g.	-	-	1	-Milk-run	-	+	+
Ramadan, Zelong Wang, and Noche (2012)	RFID-based VSM	-RFID i.g.	-	+	1	-VSM	+	-	+
Li, Zhang, and Li (2010)	RFID-based system for SPC	-RFID i.g.	-	-	1	-SPC/SQC	-	-	+
Shih and Wang (2016)	Integrating wireless sensor networks with statistical quality control to develop a cold chain system in food industries	-Wireless sensors -ZigBee	-	-	1	-SPC/SQC	-	-	+
Lee et al. (2014)	RFID-based support for SPC/SQC	-RFID i.g.	-	-	1	-SPC/SQC	-	-	+
Chen (2009)	Real-time turbine maintenance system	-RFID i.g.	-	-	1	-TPM	+	+	+
Chen and Tu (2009)	Agent-based system for manufacturing control and coordination with ontology and RFID	-RFID i.g.	-	-	1	-JiT	-	+	+
Rafique et al. 2016	RFID impacts on barriers affecting lean manufacturing	-RFID i.g.	+/-	+/-	2	-JiT -Kanban	-	+	+
Su (2009)	RFID-based Kanban system	-RFID i.g.	-	-	2	-JiT -Kanban	-	+	+
Lage Junior and Godinho Filho (2010)	Review of Kanban systems including e-Kanban	-N.s.	-	-	2	-JiT -Kanban	-	+	+
Kouri, Salmimaa, and Vilpol (2008)	User-centered design for e-Kanban system specifications	-RFID i.g.	-	-	2	-JiT -Kanban	-	+	+

Reference	Main topic (authors' perspective)	Related WT	Directly addressing lean						
			set of prin- ciples	set of wastes	Num- ber	tools/ techniques/concepts			
						Name	Purpose		
IA	II	PM							
Chongwatpol and Sharda (2013)	Discrete-event simulation of barcodes and RFID impact on wastes addressed by lean manufacturing in a job-shop setting	-RFID i.g.	-	+	2	-Kanban -JiT	+	+	+
Powell and Skjelstad (2012)	The role of RFID in extended lean enterprise in relation to 5 lean principles, application of e-Kanban, prospects for heijunka	-RFID i.g.	+	-	2	-JiT -Kanban	+	+	+
Li and Fan (2008)	JiT Distribution System Based on Web for the 3rd Party Logistics	-GPS -RFID i.g.	-	-	2	-JiT -Supplier integration	-	+	+
Zelbst et al. (2014)	Impact of RFID and information sharing on JiT, TQM and operational performance	-RFID i.g.	-	-	2	-JiT -TQM	+	+	+
Huang, Wright, and Newman (2009)	Wireless manufacturing, RFID-based Kanbans and TPM	-WT i.g. -RFID i.g.	-	-	2	-Kanban -TPM	+	+	+
Chen and Chen (2014)	RFID-based VSM	-pRFID -RFID LF -Wi-Fi 2.4GHz	-	-	2	-Kanban -VSM	+	-	+
Chen, Chen, and Cox (2012)	RFID-based VSM	-pRFID -RFID LF -Wi-Fi 2.4GHz	-	-	2	-Kanban -VSM	+	-	+
Santos et al. (2011)	WT application in TPM for improving manufacturing equipment diagnosis	-RFID i.g. -ZigBee	-	-	2	-OEE -TPM	+	-	+
Ramadan, Al-Maimani, and Noche (2017)	RFID-based VSM for cost tracking	-RFID i.g.	+/-	+/-	2	-VSM -Lean accounting	+	+	+
Tabanli and Ertay (2013)	RFID-based e-Kanban	-pRFID -RFID UHF	-	-	3	-Kanban -Heijunka -Supermarket	+	+	+
Barbosa et al. (2013)	Heijunka system in construction industry	-WC i.g.	-	-	3	-Andon -Heijunka -Kanban	-	+	+
Kolberg, Knobloch, and Zühlke (2017)	Lean automation – interface between lean and Industry 4.0, examples of digitising Kanban, andon and heijunka	-WT i.g.	-	-	5	-Andon -Poka-yoke -Kanban -Heijunka -Supermarket	-	+	+
Maurno and Sirico (2010)	WTs for lean; lean for WTs	-WTs i.g. -WC i.g. -RFID i.g.	+	+	7	-A3 -Andon -Kanban -Kaizen -Heijunka -Supplier integration -TPM	+	+	+

## Legend:

aRFID – active RFID  
 EPC – electronic product code  
 GPS – global positioning system  
 i.g. – in general  
 IA – identification and analysis of waste  
 II – improvements implementation  
 JiT – just in time  
 LF – low frequencies  
 n.s. – not specified  
 OEE – Overall Equipment Effectiveness  
 PM – process monitoring  
 pRFID – passive RFID  
 RTLS – real time locating system  
 SPC/SQC – Statistical Process/Quality Control

TPM – Total Productive Maintenance  
 TQM – Total Quality Management  
 VSM – Value Stream Mapping  
 UHF – ultra high frequencies  
 WC – wireless communication  
 WT – wireless technology

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