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 publication. 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.

Keywords:
Lean manufacturing, wireless technology, RFID.

1 INTRODUCTION
Currently, technology may permit more complex and flexible manufacturing process to occur 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 legendary Toyota Production System (TPS) that formed the basis for lean manufacturing, long before those technologies were brought to the shop-floor [1]. 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 power 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 [2-4]. 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).

2 LEAN MANUFACTURING
The lean manufacturing concept focuses on the identification and elimination all types of waste occurring in the production processes. T. Ohno [5], the author and designer of the Toyota Production System, defined 7 types of waste: overproduction, waiting, transportation, excessive processing, inventory, motion 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.

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 competitive advantage of Japanese carmakers over American ones. The research program in particular focused on analysis and comparison of production systems. This research resulted in publications by Krafick [6], who investigated organization of assembly process and famous books [7,8], which described the following lean rules:

- Value – 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 valued added, required but non-value added, and non-value added (waste) activities.
- Value stream – the value is provided through processes. All processes should be mapped and analyzed in context of value generated by the process.
- Flow – all processes should be performed without stoppages and backflows. Process should perform according to the customer tact time.
- Pull – all processes should perform in just in time manner.
- Perfection – all activities should be performing in the perfect way. When any problem occur it should solved immediately.

Later publications placed particular emphasis on people [9]. Due to this, later publications on lean management include an additional rule – Respect People [10].

All the methods can be divided into 3 categories:
- Identification and analysis of waste e.g. causal diagrams, VSM;
• Improvements implementation e.g. 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 Lean concept. Usually they are also utilized in other approaches focused on production process improvement.

3 WIRELESS TECHNOLOGIES

There have been many attempts to define information and communications technology (ICT) [11]. 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” [12]. Even though in the literal sense IT is narrower than ICT, 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. Wi-Fi, Bluetooth, LTE, Radio Frequency Identification (RFID), GPS, GLONASS among others. WTs applicability was surveyed for many branches e.g. for healthcare [13], home and building automation [14], public safety [15], agriculture [16]. It is also of interest of industrial, manufacturing, logistics and service companies [17,18]. 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.

Mauro 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 by that 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 Gladysz [19].

Huang et al. [17], 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 in [20]. However, it is limited to applicability for intelligent transport systems and is outdated. It does not cover important technologies such as for example Li-Fi (an emerging optical wireless communication [21], and some foresee it to even replace Wi-Fi networks [22]).

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 support 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.

4 WIRELESS TECHNOLOGIES FOR LEAN

4.1 Background

As lean and ICT are 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 [23]. Nicoletti [24] proposed and verified a framework for an integrated approach to process improvement including lean and ICT. Bell and Orzen [25] 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 in [26].

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 [27]. Huang et al. [17] 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 addresses directly only Just in Time (RFID-enabled kanbans) and Total Productive Maintenance concepts. However, the study could be updated due to rapid development of WTs. Considering WTs as a subgroup of ICTs, there are two dimensions of WTs and lean integration (per analogy to [25]) i.e. outward-facing lean WT (WT for lean) and inward-facing lean WT (lean for WT). Kolberg [30] presented use cases of 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 WT-related projects, programs, organizations are out of the scope of this paper. However, there are also many examples of such lean WT integration e.g. [26]. An example of parallel applications of both lean for WT and WT for lean was given in [28], 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 waste occur [3] i.e. replicate data stored in multiple places, improper application of tools, risk associated with improperly secured wireless transmissions.
4.2 Literature review

Methodology

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. Initial searching query was:

(“lean” AND (“manufacturing” OR “production” OR “manager” OR “managing” OR “thinking” OR “techniques” OR “tools”)) AND ( “wireless” OR “RFID” OR “RTLS” OR “Industry 4.0” )

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, milk run, pok-a-yoke (error proofing), SMED, SPC, SQC, supermarket, TPM, visual management, VSM. 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 i.e. lean healthcare [38,39] or lean administration. Date of publication was not an exclusion criterion. We also reviewed reference lists of found articles for important references missed in databases search.

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

Papers addressing lean in general

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 Sklejstad [29] 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 [3,29] shows clear relations between specific wireless technologies and specific lean tools. Kolberg [30] approached integration of 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 help to eliminate 7 wastes [31-33]. Rafique et al. [34] 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 [35]. Similar conclusions from two case studies of multi-national FMCG companies were presented in [36], where an analytical toolset for RFID opportunity analysis was also introduced. 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 [37] 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.

Table 1. Statistics of analyzed papers.

<table>
<thead>
<tr>
<th>Papers addressing</th>
<th>Number</th>
<th>Percentage</th>
<th>Papers addressing</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>details of WT</td>
<td>8</td>
<td>22%</td>
<td>identification and analysis of waste (I&amp;A) tools/ techniques/ concepts</td>
<td>17</td>
<td>47%</td>
</tr>
<tr>
<td>lean principles' set</td>
<td>5</td>
<td>14%</td>
<td>improvements implementation (II) tools/ techniques/ concepts</td>
<td>23</td>
<td>64%</td>
</tr>
<tr>
<td>lean wastes' set</td>
<td>7</td>
<td>19%</td>
<td>process monitoring (PM) tools/ techniques/ concepts</td>
<td>31</td>
<td>86%</td>
</tr>
<tr>
<td>0 lean tools/ techniques/ concepts</td>
<td>1</td>
<td>3%</td>
<td>I&amp;A, II and PM tools/ techniques/ concepts</td>
<td>11</td>
<td>31%</td>
</tr>
<tr>
<td>1 lean tool/ technique/ concept</td>
<td>16</td>
<td>44%</td>
<td>I&amp;A and II tools/ techniques/ concepts</td>
<td>11</td>
<td>31%</td>
</tr>
<tr>
<td>2 lean tools/ techniques/ concepts</td>
<td>15</td>
<td>42%</td>
<td>I&amp;A and PM tools/ techniques/ concepts</td>
<td>15</td>
<td>42%</td>
</tr>
<tr>
<td>3 and more lean tools/ techniques/ concepts</td>
<td>4</td>
<td>11%</td>
<td>II and PM tools/ techniques/ concepts</td>
<td>21</td>
<td>58%</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS AND IMPLICATIONS

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. It has been indicated that WT have a practical impact for the utilization of lean methods and tools. 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. WT can have both positive and negative implications (can generate waste, e.g. redundant information).

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 take into account 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.

6 REFERENCES

[32] Haddad A., Dugger J.C., Lee H., Lean Manufacturing Control, Asset Tracking, and Asset Maintenance: Assessing the Impact of RFID Technology Adoption,


[64] Barbosa G., Andrade F., Biotto C., Mota B., 2013, RFID and information sharing to develop a cold chain system in food industries, Computer Standards and Interfaces, 2016, 45, 62-78.
## APPENDIX A

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Related WT</th>
<th>Directly addressing lean principles</th>
<th>Number</th>
<th>Directly addressing lean tools/techniques/concepts</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>[36]</td>
<td>RFID i.g.</td>
<td>– +</td>
<td>0</td>
<td>–</td>
<td>– – –</td>
</tr>
<tr>
<td>[40]</td>
<td>pRFID; UHF</td>
<td>– –</td>
<td>1</td>
<td>VSM</td>
<td>+ – –</td>
</tr>
<tr>
<td>[41]</td>
<td>pRFID; UHF; EPC</td>
<td>– –</td>
<td>1</td>
<td>VSM</td>
<td>+ – –</td>
</tr>
<tr>
<td>[42]</td>
<td>WC i.g.</td>
<td>– –</td>
<td>1</td>
<td>Andon</td>
<td>– – +</td>
</tr>
<tr>
<td>[43]</td>
<td>N.s.</td>
<td>– –</td>
<td>1</td>
<td>Poka-yoke</td>
<td>– + –</td>
</tr>
<tr>
<td>[44]</td>
<td>WC i.g.</td>
<td>– –</td>
<td>1</td>
<td>Poka-yoke</td>
<td>– + –</td>
</tr>
<tr>
<td>[45]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>1</td>
<td>JiT</td>
<td>– – +</td>
</tr>
<tr>
<td>[46]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>1</td>
<td>JiT</td>
<td>+ + +</td>
</tr>
<tr>
<td>[47]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>1</td>
<td>JiT</td>
<td>+ + +</td>
</tr>
<tr>
<td>[48]</td>
<td>RFID i.g.; aRFID; RTLS</td>
<td>+/-</td>
<td>–</td>
<td>1</td>
<td>Kanban</td>
</tr>
<tr>
<td>[31]</td>
<td>RFID i.g.</td>
<td>– +</td>
<td>1</td>
<td>VSM</td>
<td>+ – +</td>
</tr>
<tr>
<td>[49]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>1</td>
<td>SPC/SQC</td>
<td>– – +</td>
</tr>
<tr>
<td>[50]</td>
<td>Wireless sensors; ZigBee</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>SPC/SQC</td>
</tr>
<tr>
<td>[51]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>1</td>
<td>TPM</td>
<td>+ + +</td>
</tr>
<tr>
<td>[52]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>1</td>
<td>JiT; VSM</td>
<td>+ + +</td>
</tr>
<tr>
<td>[53]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>2</td>
<td>JiT; VSM</td>
<td>+ + +</td>
</tr>
<tr>
<td>[54]</td>
<td>RFID i.g.</td>
<td>+/-</td>
<td>+/-</td>
<td>2</td>
<td>JiT; Kanban</td>
</tr>
<tr>
<td>[55]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>2</td>
<td>JiT; Kanban</td>
<td>+ – +</td>
</tr>
<tr>
<td>[56]</td>
<td>n.s.</td>
<td>– –</td>
<td>2</td>
<td>JiT; Kanban</td>
<td>– + +</td>
</tr>
<tr>
<td>[57]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>2</td>
<td>JiT; Kanban</td>
<td>+ – +</td>
</tr>
<tr>
<td>[58]</td>
<td>RFID i.g.</td>
<td>– +</td>
<td>2</td>
<td>Kanban; JiT</td>
<td>+ + +</td>
</tr>
<tr>
<td>[59]</td>
<td>RFID i.g.</td>
<td>+ –</td>
<td>3</td>
<td>JiT; Supplier integration</td>
<td>+ + +</td>
</tr>
<tr>
<td>[60]</td>
<td>GPS; RFID i.g.</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>JiT; Supplier integration</td>
</tr>
<tr>
<td>[61]</td>
<td>RFID i.g.</td>
<td>– –</td>
<td>2</td>
<td>OEE; TPM</td>
<td>+ – +</td>
</tr>
<tr>
<td>[62]</td>
<td>RFID i.g.; ZigBee</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>VSM; Lean Accounting</td>
</tr>
<tr>
<td>[63]</td>
<td>pRFID; UHF</td>
<td>– –</td>
<td>2</td>
<td>Kanban; Supplier integration</td>
<td>+ + +</td>
</tr>
<tr>
<td>[64]</td>
<td>WC i.g.</td>
<td>– –</td>
<td>3</td>
<td>Andon; Heijunka; Kanban</td>
<td>– + +</td>
</tr>
<tr>
<td>[30]</td>
<td>WT i.g.</td>
<td>– –</td>
<td>5</td>
<td>Andon; Poka-yoke; Kanban; Heijunka; Supplier integration</td>
<td>+ + +</td>
</tr>
<tr>
<td>[3]</td>
<td>WTs i.g.; WC i.g.; RFID i.g.</td>
<td>+</td>
<td>+</td>
<td>8</td>
<td>A3; Andon; Kanban; Kaizen; Heijunka; Poka-yoke; Supplier integration</td>
</tr>
</tbody>
</table>

Legend:
- aRFID – active RFID
- EPC – electronic product code
- GPS – global positioning system
- i.g. – in general
- I&A – 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
- UHF – ultra high frequencies
- VSM – Value Stream Mapping
- WC – wireless communication
- WT – wireless technology