Smart Dust in the Industrial Economic Sector – On Application Cases in Product Lifecycle Management

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Abstract. Smart dust is an autonomous sensing, computing, and communication system that can be packed into a cubic-millimeter mote to form the basis of integrated, massively distributed sensor networks. The purpose of this manuscript is to identify potential applications of smart dust in product lifecycle management with a focus on the industrial economic sector. Resting upon empirical data from the European DACH region, we describe six applications: (1) Advancement of requirements engineering, (2) Improvement of manufacturing processes, (3) Enhancement of logistics monitoring, (4) Optimization of operations, (5) Ameliorated maintenance and repair processes, and (6) Augmented retirement planning. Bearing the exploratory, qualitative approach and early-stage character of applications in mind, we can reason that smart dust offers great potentials to both product lifecycle management and research on it.

Keywords: Smart Dust, Industrial Economic Sector, Applications, Product Lifecycle Management, PLM, Case Study Research.

1 Introduction

Product lifecycle management is the common thread of all product- and service-related activities over the lifecycle [1,2]. As inherently neutral approach, novel technologies have been steadily cultivating product lifecycle management [1,2]. For instance, the advent of intelligent products led on to closed-loop product lifecycle management [3,4]. Another example refers to the massive digitization of products and processes, which gave rise to big data in product lifecycle management [5,6]. In line with this reasoning, smart dust [7,8] holds the potential to serve as another powerful technology supporting product lifecycle management. In detail, smart dust is an “autonomous sensing,

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[1] Parts of this manuscript draw on modified, updated, and rewritten content from the unpublished research proposal “Smart Dust - Exploring Technology Affordances in the Industrial Economic Sector” of the Swiss National Science Foundation “Spark” program.

computing, and communication system that can be packed into a cubic-millimeter mote (…) to form the basis of integrated, massively distributed sensor networks" [8:2].

The past decades have seen a rapid development of technical research to shrink the technology based on few lighthouse applications [9,10]. In comparison, only few scholars have dealt with systematic research into the role of smart dust for our daily lives [9,10]. The purpose of this manuscript is to identify potential applications of smart dust in product lifecycle management with a focus on the industrial economic sector. Therefore, we report from a foundational project of the Swiss National Science Foundation and draw on empirical data [11,12] from the European DACH region. At that, we focus on foundational innovation potentials, ideating value-adding use cases with adopters and placing arising technological impediments back.

In linkage to this prior 'Introduction', the manuscript continues with the 'Background', where the foundations of smart dust and related work are rolled out. The subsequent 'Methodology' unfolds the research strategy and data gathering and evaluation. The 'Findings' in the style of a lifecycle-oriented illustration followed by the 'Discussion' represent the main part. The 'Conclusion' finalizes this manuscript with a summary, contributions, limitations, and an outlook.

2 Background

Foundations. Despite its visionary character, the roots of smart dust reach surprisingly far back into the past [7,8]. Around the 1990s, Silicon Valley-based UC Berkeley scholars Pister and Kahn coined the term for these miniaturized micro-electro-mechanical systems [9]. Structurally, smart dust is composed of corresponding motes, which in turn are compounded by the sub-components energy supply, sensing elements, computing capacity, and communication capabilities [13]. Regarding this technical anatomy, a spectrum of approaches exists: One-time (e.g., miniaturized batteries) and periodic (e.g., solar cells, energy harvesting) supply provides adequate energy [8]. Sensor modules for almost every physical variable enable the sensing [8]. Traditional methods target to reduce computing times at a given size, whereas down scaled computing focuses on energy reduction, for instance by novel transistors [8]. Optical or communication by radio waves allows for an information exchange with other motes or systems [8]. While smart dust crystallized as main term [10], nearby concepts emerged. Brilliant rocks [9] exhibit externally sensing and reusable character, micro-robots [8] complement their sensing abilities with actuating capabilities, and also communicating materials [14] are known. Upon this interdisciplinary character, scholars revert and contribute to a plethora of research disciplines [10]. We executed a literature review following the advices by Webster and Watson [15] to untangle the relevant body of knowledge. Thereby, we seek to consider both, academia and industry.

Related work. With regard to the academic status quo, much of the available literature deals with the introduction of the concept and technology itself [7,8]. In technical terms, authors have been mainly interested in specific questions concerning issues such as communication [16]. With regard to economic aspects, others have highlighted the relevance of applications in general engineering, agriculture and environmental monitoring, civil engineering, as well as health monitoring and surgery, and – as many modern technologies – in the military [10]. For instance, Satyanarayanan [9:2] pictures: “If you added a handful of smart dust to every batch of concrete as it is mixed, the resulting buildings would essentially have a nervous system built into every structural element.” With regard to the industrial status quo, established (e.g., IBM, Hitachi) and aspirant (e.g., AmbiqMicro, CubeWorks) firms develop and manufacture such motes. This increasing feasibility has created an emerging eco in management magazines [17] and the impactful Hype Cycle [18].

Research gap. Speaking in terms of research gaps, following the work by Müller-Bloch and Kranz [19], a knowledge void emerges. Considering all of this evidence, only few scholars have dealt with systematic research into the role of smart dust for our daily lives [9,10]. However, both academic and industrial representatives plea for such knowledge and “real life applications” [20:25] for smart dust.

3 Methodology

Research strategy. Our goal is to identify potential applications of smart dust in product lifecycle management with a focus on the industrial economic sector. Based on the lack of knowledge in this innovative domain, the most popular research strategy for determining such uses is qualitative, exploratory research [11,12]. In greater detail, we make use of case study research [21,22], formulated as “empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident” [21:13]. Reverting to Yin’s [21] matrix, we aim for a (1) multiple-case study studying diverse companies and (2) several units of analysis, namely the activities related to product lifecycle management. Contextually, the industrial economic sector with a focus on the European DACH region as fertile, technology-depending, and innovation-affine area [23] offers an insightful starting base.

Table 1. Empirical data from the DACH region

Case company	*Characteristics*	*Sources of evidence*
OpticTech	GER, 5.000 employees	Interview Head of Prod. Design (01/2020), documents
CastingTech	GER, 200 employees	Interview Technical CEO (12/2019), documents
SpaceTech	CH, 10.000 employees	Interview Manager MRO (10/2019), documents
PipeTech	CH, 5.000 employees	Interview Head of Service (12/2019), documents
EnergyTech	CH, 10 employees	Interview CEO (02/2020), documents
TransportTech	AUT, 3.000 employees	Interview Manager MRO (10/2019), documents

Data gathering. First, regarding the data gathering, we designed a maximum variation sampling [24]. A key strength of such an approach is to lay down the playfield and illustrate the spectrum of the examined phenomenon [24]. Table 1 demonstrates the empirical data. To maximize the insights, several parameters were varied. First, in terms of cases [21], we included firms from different domains (e.g., transportation), company sizes (e.g., SMEs), manufacturing modes (e.g., ETO), and production foci (e.g., component). Second, regarding the units of analysis [21], we incorporated all stages, from beginning-of-life over middle-of-life to end-of-life [1]. For case study research, Yin [21,22] suggests a plethora of sources of evidence. Lastly, we selected interviews – well-suited for ideating and discussing the not yet implemented use cases – and documents (e.g., websites) – ideally for assessing the contextual situation [21,22]. After the communication of the research goal, we used a questionnaire [25] comprising the sections (1) Introductory questions, (2) Current situation, (3) Ideation of use cases, and (4) Outlook as conversation directive. Across the whole data collection, special emphasis was placed on foundational innovation potentials, ideating value-adding use cases with adopters and placing arising technological impediments back.

Data evaluation. Second, concerning the data evaluation, we refer to established qualitative examination practices [26,27]. Both interviews and relevant information from the documents were evidenced by use case formats [28,29]. Among other elements, a title, description, and sketches were included [28,29]. Upon the purpose, we furthermore leveraged a lifecycle-oriented theoretical lens. Several decades of research have brought a spread of corresponding lifecycle models [30]. For this manuscript, the well-established model by Terzi et al. [1] is used for systematization. In qualitative investigations, there are more sources for errors than in its quantitative pendent [11,12]. In order to reduce these uncertainties and augment the quality, we reviewed and applied corresponding recommendations for action (e.g., triangulation, cross-checking [21,22]).

4 Findings

Figure 1 shows potential applications for smart dust in product lifecycle management with a focus on the industrial economic sector. For a better understanding, we report on the most insightful applications. In what follows, each identified application is described by case company, main challenge, technical solution, obstacles, and generalizability.

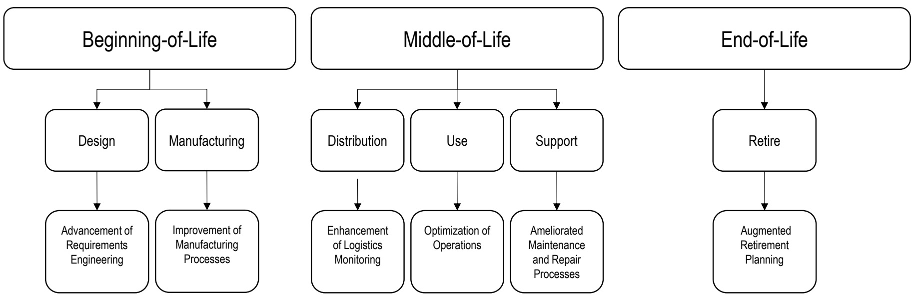

Fig. 1. Potential applications for smart dust in PLM (model by Terzi et al. [1])

4.1 Advancement of Requirements Engineering

OpticTech develops and manufactures opto-mechanics such as spectacles and spectacle frames for the high-end segment. Headquartered in Germany, a global workforce of approximately 5.000 people generates around 500 million EUR sales in B2C (private customers) and B2B (eye shops) markets. A challenge in new product development and product further development is the unknown wearing and usage behavior of spectacles. For example, even after almost 100 years in business, no detailed segment-specific information on the wearing time of glasses is available. A potential technical solution to address this shortcoming refers to the attachment of smart dust motes to the frame to monitor key parameters such as wearing times. A major advantage accrues from both enablement and refinement of design requirements in a real-life setting. The Head of Production Design reported on potential obstacles related to data privacy as glasses are part of all aspects of life. Further challenges referred to the necessary data receiving mechanism. Finally, the expected high costs compared to price of spectacles were named as another criticism. In terms of generalizability, this application seems well-suitable for various consumer and industrial products where requirements are un- or not well-known. Thus, we name a first application of smart dust in beginning-of-life (design): “Advancement of Requirements Engineering”.

4.2 Improvement of Manufacturing Processes

CastingTech produces cast pieces made of non-ferrous metals, including pre- and post-activities. As small- and medium-sized enterprise with around 200 employees based in Germany, special engineering, rail transport, and medical technology represent main segments, whereby automotive is explicitly excluded. The Technical CEO reported on unknown rheological behavior during the casting process. These insufficiently transparent material parameters (e.g., flow/cooling rate) lead to varying material properties (e.g., static/dynamic strength). Currently, the engineers apply filling simulations, however their assumptions cannot be validated. A thinkable technical solution describes the infusion of motes into the molten material to sense the casting parameters. Two strategies seem possible, an exploration of parameters in the sense of a pilot, or the continuous monitoring in series production. Critical points are apparently heavy mechanical and thermal stress. Additionally, the communication through the dense material and the impact on the material behavior remained as open points. From a financial perspective in prototypical settings acceptable, casting is named as competitive business. In the narrower sense, the application may be transferred to plastics casting (e.g., injection molding). In a wider sense, a deployment for any primary forming (e.g., 3D printing) seems possible. Hence, we define a second application of smart dust in beginning-of-life (manufacturing): “Improvement of Manufacturing Processes”.

4.3 Enhancement of Logistics Monitoring

SpaceTech represents a multi-national technology company (10.000 employees, two billion EUR sales) domiciled in Switzerland. The product and service portfolio encompasses structures and electronics for land and aerospace. Thereby, customers come from both civil and military domains. A prominent obstacle in the internal and external distribution is the transportation of sensitive components to the final assembly location. For example, the fuselage for a plane made from reinforced plastics often needs to be shipped over long distances by road to the original equipment manufacturer for final montage. As potential technological solution, the Manager MRO proposed the embedding of smart dust into the material layers or the direct integration into 3D printed structures. In this way, a granular tracking of stokes or other harmful situations during the transport is made possible. In this scenario, the extensive costs were not perceived as critical. However, concerns were raised with regard to the value-add beyond existing sensor solutions and the sufficient precision for aerospace quality. Such uses seem conceivable for further precious products in the B2B (e.g., airplanes) and B2C (e.g., art) domain. Therefrom, we determine a first application of smart dust in middle-of-life (distribution): “Enhancement of Logistics Monitoring”.

4.4 Optimization of Operations

PipeTech is a world-wide leader for industrial piping systems. As part of a larger diversified multi-national, the division offers whole system solutions, individual components, and allied services in domains such as water supply, industrial manufacturing processes, and increasingly data center cooling. For the ambitious data center cooling with guaranteed availabilities close to 100 percent, existing smart connected cooling solutions offer solely limited transparency and control possibility for the critical cooling parameters. According to the Head of Service, the limited number of measuring points causes this weakness. As imaginable technical solution, the infusion of smart dust motes into the pipe material or the transported cooling fluids was proposed. Regarding the former, steady sensing over the pipe length is made possible. Regarding the latter, even more detailed, each volume element of the fluid can be sensed. Depending on the cooling type, both mechanical or/and thermal stress appear on the scene. Generally, such thermo- and fluid-dynamic systems work after complex system dynamics, which in this way even become more intricate. With regard to a wider applicability, vast potentials emerge for further transported fluids or gaseous materials (e.g., process industries). So, we conceptualize a second application of smart dust in middle-of-life (use): “Optimization of Operations”.

4.5 Ameliorated Maintenance and Repair Processes

EnergyTech is an emerging clean tech start-up. In the order of ten employees design, assemble, and support renewable energy systems reverting to wind power. Thereby, main customers come from B2C (e.g., private homes and flats) and B2B (e.g., prime contractors, real estate management firms). Such complex industrial assets with long lifecycles bear the necessity of guaranteed availability and optimized maintenance. The CEO reported that unexpected breakdowns are often induced by low-cost parts such as sealing rings. This obstacle may be addressed by the integration of smart dust in these wearing parts. Hence, the progression of wear (e.g., plastics ageing) can be monitored in a more fine grained manner, and when necessary encountered. With regard to the challenges, such an infusion implies heavy compartmentalization and complex system behavior to predict the required maintenance and repair processes. Furthermore, wearing parts at a micro level and power generation at a macro level are considered as heavily price sensitive markets. Referring to the generalizability, this use case seems widely applicable for further mechanically critical components in any maintenance-intensive areas. Consequentially, we name a third application of smart dust in middle-of-life (support): “Ameliorated Maintenance and Repair Processes”.

4.6 Augmented Retirement Planning

TransportTech is a market leader for innovative transport systems. The multi-national with several subsidies designs, produces, installs, and maintains ropeways. Approximately 3.000 employees serve touristic mountain regions and increasingly urban areas as main customers, and generate in this way 850 million EUR revenues. In such contexts, the insecure mechanical strength after exceptional events such as storms represents a substantial obstacle. Against the background of human beings as transported good and high investments of the ropeways, it is critical to decide when to retire the ropeway equipment. A potential technical solution may be the infusion of smart dust into mechanical structures as “neural system” to measure the material characteristics at any place at any time. In doings so, a more specific end-of-life prediction can be made, also involving aspects such as local material ageing. Impediments arise from several sides. Although the benefits of traffic safety are non-discussable, an application faces high costs compared to the low occurrence probability of such events. Additionally, according to the Manager MRO, a potential impact on the material behavior seems particular critical. The application is highly generalizable as it can be transferred to any business with safety critical components (e.g., wind turbines, train powertrains). Finally, we introduce an application of smart dust in end-of-life (retire): “Augmented Retirement Planning.”

5 Discussion

Two lines are of particular interest for the subsequent discussion. We begin with fundamental discussion including a confrontation with literature, and then pass over to a systematization of the applications.

Fundamental discussion. First, regarding opportunities, evidence shows that smart dust affords great potential for the lifecycle management of industrial products. In the beginning-of-life stage, smart dust may support design and manufacturing. Distribution, use, and support is facilitated in middle-of-life. And, in the end-of-life stage, this new technology also could augment product retiring. In each stage, we could detect value-add by enabling new or improving existing functions. Second, despite these marvelous chances, a plethora of impediments emerged as well. These range from technical (e.g., mechanical/thermal stress, communication) over financial (e.g., cost/benefit) to social (e.g., data privacy) aspects. In the case of an actual realization, current product lifecycle management organizations, processes, and systems would be impacted profoundly. Contrasting the identified applications with the accomplished literature review [9,10], we are able to verify, but also to amplify these application possibilities. For instance, compared to the published gaseous uses [9,10], the field was particularly opened up towards liquid and even solid cases.

Systematization of applications. Diving more deeply into the diversity, Table 2 shows an initial classification model of smart dust applications in product lifecycle management. Therefore, we used well-established classification methods adopting Nickerson et al. [31]. We assimilate the affordance concept [32] as important meta-characteristic [31], differentiating between material properties ("How can we describe it?") and technology affordances ("What can we do with it?"). More precisely, the dimensions and its characteristics were derived by (1) literature (e.g., [7,9,13]) and the (2) empirically collected applications, as advised by Nickerson et al. [31].

Table 2. Classification model of smart dust applications in PLM (model by Chemero [32])

<table>
<tr><td colspan="4">Material properties: How can we describe it?</td></tr>
<tr><td>Carrier state</td><td>Liquid</td><td>[Solid]</td><td>Gaseous</td></tr>
<tr><td>Distribution</td><td colspan="2">[Fixed]</td><td>Loose</td></tr>
<tr><td>Capabilities</td><td colspan="2">[Sensing]</td><td>Actuating</td></tr>
<tr><td>Application period</td><td colspan="2">Temporary</td><td>[Continuous]</td></tr>
<tr><td colspan="4">Technology affordances: What can we do with it?</td></tr>
<tr><td>Value-add scope</td><td colspan="2">[Enhanced product]</td><td>Enhanced product management</td></tr>
<tr><td>Value-add level</td><td colspan="2">[Enabler]</td><td>Refiner</td></tr>
</table>

As we can see, the material properties show a great variety. In terms of carrier state, the smart dust motes may be infused in liquid, solid, or gaseous materials. However, phase transitions (e.g., casting processes) are possible. Looking at the distribution, fixed and loose embedding is suitable to describe this dimension. Regarding the capabilities, only sensing uses appeared, but actuating capabilities (e.g., adaptive pipes) are conceivable as well. In regard to the application period, a temporary or continuous deployment of the motes is possible. Furthermore, also the technology affordances exhibit remarkable variances. In the most simple sense, smart dust affords an enhanced product (e.g., tailored spectacles) or an enhanced product management (e.g., monitored logistics). Describing the value-add level, both enabling and refining opportunities became apparent. For illustrative purposes, we selected an exemplary application ("Advancement of Requirements Engineering" by OpticTech) and highlighted the corresponding characteristics by brackets.

6 Conclusion

The purpose of this manuscript is to identify potential applications for smart dust in product lifecycle management with a focus on the industrial economic sector. Resting upon empirical data from the European DACH region, we describe six applications: (1) Advancement of requirements engineering, (2) Improvement of manufacturing processes, (3) Enhancement of logistics monitoring, (4) Optimization of operations, (5) Ameliorated maintenance and repair processes, and (6) Augmented retirement planning. As bottom line, we can reason that smart dust offers great potentials to both product lifecycle management and research on it.

Up to the authors' knowledge, this contribution is the first time that this technology is proposed for use in product lifecycle management. By overcoming anecdotal use cases (e.g., [9,10,33]), this manuscript contributes to a fine-grained, empirically-based, and lifecycle-oriented lineup. We hope that our findings acquire vogue in manifold contexts. For researchers in the scientific community on product lifecycle management as an overview and inspiration [34], for industrial developers and users of product lifecycle management as technology scouting [35], and finally for the society for a sensitization on such disruptive technologies [36].

Despite the valuable results, this manuscript is exposed to limitations, which should be disclosed fairly and squarely. A major limitation emerges from the exploratory, qualitative approach [11,12] offering deep insights, however no widely generalizable results. Another relevant restriction is associated with the early-stage character, as presently no functional smart dust applications exist where real benefits could be shared to the reader.

Research on smart dust and its relationship to product lifecycle management is by far not depleted. Product lifecycle management and affecting emerging digital technologies are understood as socio-technical phenomenon [37], thus both sides need to be deepened. In terms of social impact, there is great research potential for additional applications of smart dust. For example, diving one level deeper into the lifecycle model (e.g., product design, process design, plant design, [1]) may bring out further uses. With regard to the technical foundation, first applications may be prototyped to collect real-world experiences. As base, however, the feasibility (e.g., energy supply and communication in solids) needs to be evaluated.

Acknowledgements. The authors of this research paper were supported by the Swiss National Science Foundation "Spark" program.

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