Journal of Cleaner Production xxx (2014) 1–15

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Addressing sustainability in research on distributed production: an integrated literature review

Cindy Kohtala*

Aalto University School of Arts, Design and Architecture, Helsinki, Finland, NODUS Sustainable Design Research Group, PO Box 31000, FI-00076 Aalto, Finland

A R T I C L E I N F O

Article history:
Received 24 October 2013
Received in revised form
22 August 2014
Accepted 6 September 2014
Available online xxx

Keywords:
Distributed production
Environmental sustainability
Fab labs
Mass customization
Literature review

A B S T R A C T

This paper presents an integrated literature review on how the environmental sustainability of distributed production is studied in a variety of disciplinary sources. The notion of distributed production suggests an alternative to mass production that differs in scale, location and consumer–producer relationship. Understanding its environmental implications (and thereby dematerialization potential) is regarded pertinent and timely. Key themes in the review included how distributed production can promote product longevity and closed material loops, as well as localizing production. New and closer ties between producer and consumer seemed central discussions but were underdeveloped with regard to sustainability potential. Empirical work was seen especially in research on Additive Manufacturing Processes, while the bulk of the studies were conceptual explorations with little testing in the real world as yet. This affirms the emerging nature of the topic and points to a clear need for more (and more diverse) empirical research. The review summarizes the opportunities for greater environmental sustainability as well as potential threats that could serve to guide and improve these novel practices today. It sets the stage for 'distributed production' to be examined as its own phenomenon by proposing how it can be characterized and suggests that a research agenda could build upon the work initiated here.

1. Introduction

The notion of *distributed production* conceptualizes a shift in consumption and production patterns away from conventional mass production, with its long, linear supply chains, economies of scale and centralizing tendencies. The boundary between consumers' and producers' roles blurs and the intermediaries between them disappear or transform. Drivers for such reconfigurations include benefits for producers in terms of cost or competitiveness (Jiang et al., 2006; Piller et al., 2004). Distributed production thus includes a range of current and emerging practices where private citizens have increased capacity to affect what is produced, from product personalization to personal fabrication.

Such an alternative structure, even paradigm, should also have the potential to be leaner and cleaner, mitigating or eliminating the social and environmental problems associated with mass production. This raises the question of what knowledge currently exists on the sustainability of distributed production and how the research community is approaching the acquisition (and implementation) of such knowledge.

This paper presents an integrated literature review that examines what aspects of distributed production researchers are studying when they aim to establish links to sustainability beyond simply economic sustainability. As there is not yet a clear, agreed understanding of "distributed production" as such, the review targeted several research fields studying decentralized, networked alternatives to mass production.

Practices that integrate production and consumption are not new, but today they are especially enabled by (and thereby defined by) advances in digital manufacturing technologies and the internet (Kumar, 2007; Marsh, 2012). These activities are now evolving and entering the mainstream, from customization and

Abbreviations: 3DP, 3D-Printing; AM, Additive Manufacturing; DIY, Do It Yourself; EIA, Environmental Impact Assessment; EOL, End of Life; IE, Industrial Ecology; IM, Injection Moulding; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; MC, Mass Customization; MCP, Mass Customization and Personalization; MP, Mass Production; OSAT, Open Source Appropriate Technology; PSS, Product-Service System; RM, Rapid Manufacturing; RP, Rapid Prototyping; RT, Rapid Tooling; SLS, Selective Laser Sintering.

* Tel.: +358 50 564 0400.
E-mail address: cindy.kohtala@aalto.fi.

http://dx.doi.org/10.1016/j.jclepro.2014.09.039
0959-6526/

personalization to co-production or personal fabrication of goods. Whether such a shift in production mode can help dematerialize current consumption is uncertain; it can thus be argued that the sustainability assessment of these practices is best done sooner than later.

2. Theory and background

In engineering and operations management, distributed production is often a synonym for distributed manufacturing (Windt, 2014) and takes the perspective of production planning for networked or "virtual" enterprises aiming for flexibility, agility and greater customer orientation in manufacturing and mass customization (Bruccoleri et al., 2005; Leitão, 2009; Tuma, 1998). Agility is a key characteristic, as the term *distributed* has its roots in computing and communications, when a more robust network that distributed nodes rather than centralizing or decentralizing hubs or switches was developed (Baran, 1964; Windt, 2014).

It is also a term used more widely ideologically as well as epistemologically, when discussing alternative business models and opportunities for more socially beneficial and responsive production and consumption. The notion of "distributed economies" promotes small-scale, flexible networks of local socio-economic actors using local resources according to local needs, in the spirit of sustainable development (Johansson et al., 2005).

The blurring between production and consumption, another key characteristic of distributed production, may instead be referred to as "prosumption" and the consumer a "prosumer" (Toffler, 1980), for whom production becomes part of the consumption process. When prosumption involves peer-to-peer networks, some researchers refer to the practice as "commons-based peer production" (Benkler, 2006). Prosumption and peer production have been examined from the perspectives of, for instance, markets (Xie et al., 2008), behavioural science (Ritzer et al., 2012), consumer research (Ritzer and Jurgenson, 2010) and Marxist critique (Moore and Karatzogianni, 2009). This research has especially focused on digital artefacts and internet-based initiatives, but distributed peer production of tangible products is attracting increasing interest in research and practice.

In the current study, material, physical goods as the output of distributed production call particular attention to appropriate, responsible and equitable use of materials and energy. Moreover, the most novel activities relevant in this study are for some the most intellectually compelling and for others potentially the most disruptive: that is, "personal manufacturing" (Bauwens et al., 2012), "personal fabrication" or "fabbing" (Gershenfeld, 2005), "commons-based peer production of physical goods" (Troxler, 2013) or simply "making" (Anderson, 2012; Gauntlett, 2013; Hatch, 2013). For these reasons this literature review has selected the lens of distributed production's *environmental* sustainability, not to the exclusion of the social and economic dimensions but rather foregrounding the environmental issues.

As mentioned, research in this area does not yet have a common understanding of the phenomenon (or phenomena), and terminology, success factors, indicators, system boundaries and units of analysis vary from field to field. A survey that aims to map the topic of distributed production is therefore deemed valuable, especially in view of its potential as a new and more sustainable paradigm. This enables a better understanding of how researchers regard distributed material production in relation to a more sustainable present or future, how environmental sustainability principles are operationalized or theorized, and what methods and data are seen as tools to study the phenomenon.

The literature review described in this paper undertook to examine three research questions:

- what fields, disciplines or specialists are discussing distributed production and how they are addressing it;
- how sustainability is represented and the nature of the relationship between environmental sustainability and distributed production; and
- what research gaps currently exist as well as what research directions are most promising.

The results reveal the current research landscape, the main topics of concern and point to opportunities for further research as well as improved practices. The methods by which the review was conducted are described in the following section.

3. Methods

The choice of an integrated literature review refers to a review that describes and synthesizes the knowledge from diverse sources (Whittemore and Knafl, 2005). It is especially appropriate for new subjects where incorporating several theoretical domains is seen as a strategy to developing new conceptual models, research agendas and/or metatheories (Torraco, 2005). This is in contrast to systematic literature reviews which generally aim for a complete compendium of the literature, especially in a mature topic and often from the perspective of one knowledge domain. In the latter the search for peer-reviewed journal articles is therefore often done via databases.

In this study an integrated review allowed for more considered selection and inclusion of varied data sources, theoretical as well as empirical, and emphasis on portraying a complex concept through a diverse and broad sampling frame (Whittemore and Knafl, 2005). The objective was to target representative (rather than comprehensive) channels of research, including both journals and conferences, that reached the most relevant audiences and would have high potential in the researcher's estimation to examine aspects of distributed production and its environmental sustainability.

The study therefore first identified the target sources as well as the target keywords. The journals were selected according to field and impact factor, the conferences according to the field(s) represented and the conference organizers' intention to combine research and practice (bridging academia and commerce). This approach allowed one researcher to better tackle the screening process and ensure rigour in the literature search stage, especially considering the challenging lack of consensus on terminology.

The diagram in Fig. 1 depicts the target journals' scientific areas, indicating how they were selected to represent as wide a spectrum as possible (while acknowledging that journals and their individual published studies may be cross-disciplinary). The scientific areas are based on a mapping of scientific communications as described in Rosvall and Bergstrom (2011). No journal from the Life Sciences was examined, as any relevant theories or knowledge (on e.g. consumer psychology) are likely to be incorporated into other studies, as is the case in some design or consumer research, for instance. Design, production, consumption and environmental studies were regarded as relevant starting points. The full list of journals and conferences selected is found in Appendices A and B.

The topical scope of the literature search is depicted in Fig. 2. The target was a spectrum of distributed prosumption activities as the focus of research, where the consumer (customer, user, prosumer or 'maker') is able to intervene in design and production to a greater extent than in mass production, resulting in a tangible artefact. This increased agency, integration or input ranges from personalized options in a mass customizing or distributed manufacturing service to fabbing: machine-aided self-fabrication of one's own design, e.g. in a Fab Lab (a space equipped with small-scale digital manufacturing equipment the individual operates herself) (Gershenfeld, 2005).

Please cite this article in press as: Kohtala, C., Addressing sustainability in research on distributed production: an integrated literature review, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.09.039

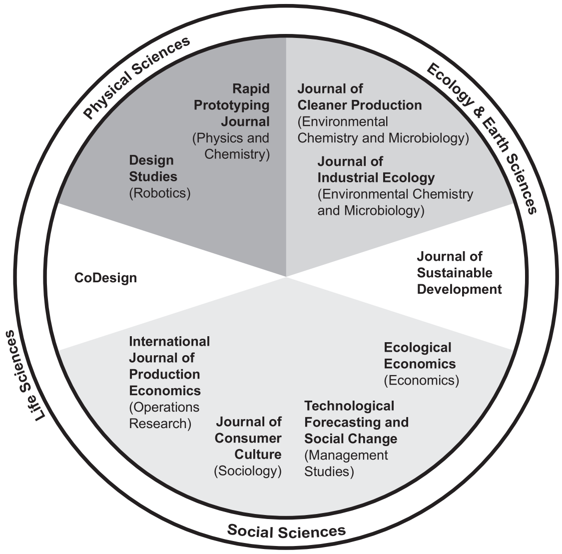

Fig. 1. The journals targeted in this review and their scientific research fields. (Eigenfactor categories are given in brackets.)

Regarding sustainability, it was hypothesized that research on these activities would address various environmental aspects. Study topics and their objectives may include less impactful supply chains (see e.g. Huang et al., 2013), cleaner manufacturing processes (e.g. ATKINS Project, 2007) and/or overall less material flow.

The relevant keywords for the review therefore included *distributed production*, *distributed manufacturing*, *mass customization*, *personalization*, *peer production*, *prosumption*, *fabbing*, *personal fabrication* and *Fab Labs*, but the selection process was not restricted to these keywords, given the wide range of terminology actively used. Instead the titles, abstracts and keywords of all full papers (and full paper itself where necessary) were examined for relevance to the *topics* (i.e. synonyms and comparable constructs, not simply keywords). The procedure aimed to capture activities and operations as well as technologies (i.e. digital fabrication, especially *additive manufacturing*). With regard to environmentally relevant issues, the assumption was that 'sustainability' must be important enough that it was directly addressed in the title or abstract (by the words *sustainability*, *environment* or *green*) and not hidden within the contents of the paper. The timeframe for the literature collection was the decade from 2002 to 2012, as before this time there was little or no interface between these technologies and services and private citizens.

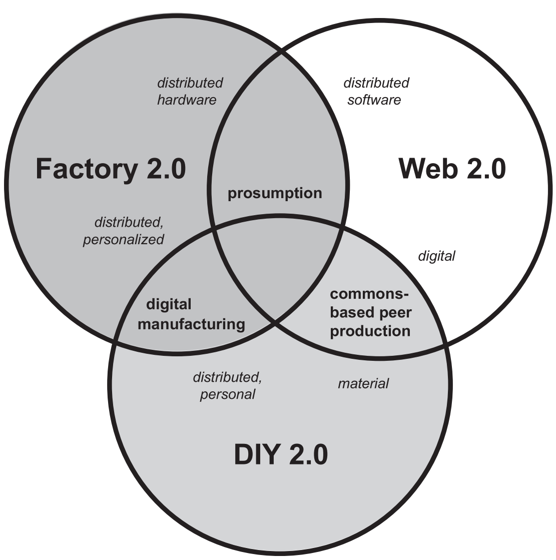

Fig. 2. The contents scope of this literature review (in grey). The review focused on material products and excluded digital artefacts (as produced in 'Web 2.0'). It took into account digital manufacturing capabilities in production: in distributed 'Factory 2.0' activities (thereby excluding traditional mass manufacturing) and digitally enabled, personal 'Do-It-Yourself 2.0' production (thereby excluding conventional handicraft).

The screening excluded editorials, commentaries, book reviews and special issue introductions. Many studies on peer production or prosumption unsurprisingly focused on digital artefacts (such as Wikipedia) or services such as health or tourism, which were excluded. Despite their prevalence in additive manufacturing, studies relating to biomedical applications, automobiles and aerospace were excluded, as being too far removed from the realm of consumer input (i.e. prosumption). Finally, papers related to food were deemed out of scope and those relating to housing and construction out of scale for this review.

To ensure that all relevant papers had been identified, a keyword search using each journal's search function was conducted at the end of the literature search stage. The keywords used were the same used to scan the contents of titles and abstracts as described above (the words in italics and their variants). Moreover, these keywords were entered into the EBSCO Academic Search Elite database and the results screened for relevance. Finally, the reference lists of the relevant papers were examined. These procedures did not yield any new critical sources, especially not the new subject perspectives sought (such as economics or marketing studies). The most *representative* coverage possible was considered accomplished, yielding a total of 29 papers.

In analysis, a table (or concept matrix) (Webster and Watson, 2002) served to list the key themes and summaries for each paper in a qualitative and descriptive format, based on the research questions. The objective was to clarify what aspects of distributed production researchers are studying and how they proceed to examine it, as well as what seems to be *known* about the topic. The table was divided into two parts. Besides general categories such as intended audience, type of paper, method, focus and unit of analysis, and nature of the empirics, the first part of the table summarized how each paper represented distributed production; the user and the relationship between user/consumer and producer; sustainability; and the relationship between the production mode and sustainability.

The second part of the table listed themes that arose from the papers themselves inductively: the authors' own concerns, stated implications and suggestions for future research. It also listed the researcher's own notions on implications and research gaps not discussed by the authors, as well as remarks on, for example, the quality of the paper[1] and the most salient links to other papers in the review. Finally, three to four keywords were ascribed to each paper independent of its own keywords.

This tabulation resulted in (a) a taxonomy or categorical grouping of the papers according to main study focus and audience or research area, as described in Section 4.2, and (b) a collection of the most salient themes amongst the authors, as described in Section 4.3. A content map (as described in Hart, 1998) was then constructed with two aims: in synthesis, to better depict the relationships among the 29 studies, and to illustrate the current

[1] While the perceived validity of the papers had not been a screening factor (non-peer-reviewed conference full papers were included), this was accounted for and studies of deemed lower quality were taken less into consideration in the analysis (Whittemore and Knafl, 2005).

Please cite this article in press as: Kohtala, C., Addressing sustainability in research on distributed production: an integrated literature review, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.09.039

'landscape' of distributed production as both a phenomenon and research subject (Fig. 4). A second map outlined the environmental sustainability issues as discussed by the authors (Fig. 5). These content maps are described in Section 4.4. Sections 5 and 6 then discuss the review's main contributions and implications.

4. Results

The group of 29 reviewed papers is listed in Table 1. The papers are accorded an identifier consisting of a number and its source in an abbreviation which will be used throughout this review.

4.1. General summary of results

All authors of the reviewed papers were based in universities and research institutes, from Europe, the Americas (the US, Canada and Brazil) and the Pacific region (Japan, Malaysia and New Zealand). The vast majority of authors were based in Europe (especially Germany, the UK and Italy).

By far the majority of authors and their intended audiences represented fields that could be described as operations and production management, environmental management and/or design and engineering. Several design studies incorporated sociological perspectives on consumption and identity. Two papers aimed to also reach a policy or regional development audience and one addressed international development. About half (15/29) of the papers were from the Mass Customization, Personalization and Co-creation (MCPC) conferences; five of these were linked to projects and reported on interim results. Many seemed to be initial reports of studies that would later be turned into journal papers or theoretical explorations serving as a platform for later empirical study. Several authors would indeed later appear as contributors to book chapters, notably in Piller and Tseng (2009) and Poler et al. (2012).

Three points may be distinguished regarding this collection of studies. First, it is important to note that no authors used the term "distributed production" as such, with the exception of Manzini (2009) [15-DS] (who referred to "distributed systems"), even as all recognized differences from mass production in their focus area regarding production locations, facility and/or batch sizes, the role and integration of the consumer, and/or the configuration of the supply chain. Preferred terms were mass customization, customization or personalization in the majority of cases (and even art customization in one paper); prosumer in several papers and prosumption as the main term in one study; and fabbing as the main term in one paper.

The second factor of note is the exploratory and propositional nature of many papers.[2] There were relatively few empirical studies and dominant was a sense of model-building and sense-making in order to better inform operational practice. In these conceptual explorations, there was little or no real-world testing reported; existing literature or secondary data from other studies often served as data sources. Where primary data was gathered, it was in the form of lab experiment results (quantitative)[3]; "action research" results[4]; surveys (qualitative and quantitative), interviews (qualitative) and a Delphi study (qualitative and quantitative)[5]; and design experiments and other descriptive material resulting in case-study-type accounts.[6] The tendency to present frameworks and propositions without explaining the observations or experiences that led to them is partly due to the large number of conference papers represented, but it is also likely due to the novelty of the topic.

Related to this novelty is the third factor of note, the scant number of papers that actually address distributed production *and* sustainability. To illustrate this ratio, the number of relevant reviewed papers was compared to the total number of published papers in each journal. The number of relevant conference papers, presentations and session topics that addressed sustainability as compared to the total number was also noted and tallied. These figures are listed in Appendices A and B.

4.2. Topical categories of the reviewed papers

This section describes the results of the first analysis and grouping stage. The three main categories will be discussed in order of their granularity, the first category of studies addressing the process- and technique-specifics of more environmentally friendly practices in additive manufacturing, geared especially to production engineers. The second category of studies, the largest group, addressed production planning and evaluation in mass customization processes, aimed especially at engineers and designers of both products and systems. The third category was more future-oriented and transdisciplinary, studies examining personal fabrication (fabbing) and peer-to-peer production, aimed at various audiences(See Fig. 3).

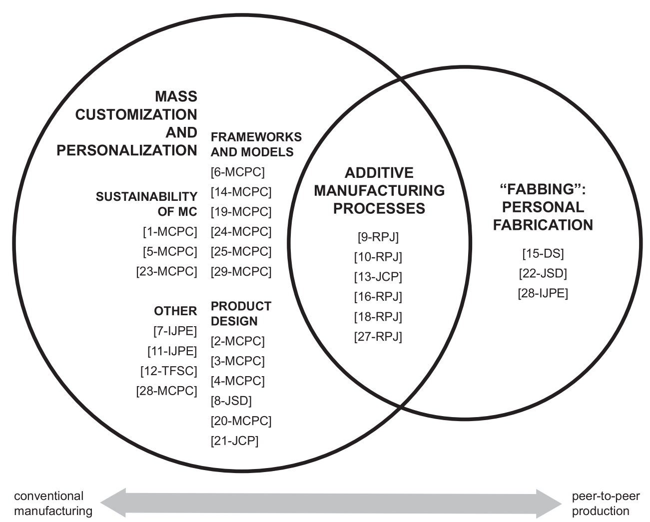

Fig. 3. Categorization of papers and their research topics. The Mass Customization and Personalization category (on the left, with sub-categories) represented activities that are nearer conventional manufacturing than peer-to-peer production. The smallest group was the 'Fabbing' category describing personal fabrication and peer production activities (on the right). Bridging these two categories are the technologies themselves, with a distinct category of papers studying Additive Manufacturing Processes (in the middle).

4.2.1. Additive Manufacturing Processes

Six papers in this review approached sustainability in distributed production by drawing attention to processes or materials in additive manufacturing (AM) or rapid prototyping (RP) (Table 2). The context of this research was mainly industrial scale and the AM systems discussed in these papers mainly for prototype or component fabrication. These studies were nevertheless included in this review as AM technologies are increasingly relevant to mass customization (the MCPC conferences have sessions devoted to AM) as well as services or facilities offered in peer production (fabbing).

[2] i.e. papers 1, 2, 5, 6, 8, 14, 15, 17, 19, 22–25, 29.
[3] Papers 9, 13, 16, 18, 27.
[4] Paper 12.
[5] Papers 7, 20, 21, 28.
[6] Papers 3, 4, 26.

Franco et al. (2010) [13-JCP], Mognol et al. (2006) [18-RPJ] and Telenko and Seepersad (2012) [27-RPJ] focused on electricity consumption and energy efficiency; Dotchev and Yusoff (2009) [9-RPJ] and Marchelli et al. (2011) [16-RPJ] on material recycling and optimization; and Drizo and Pegna (2006) [10-RPJ] on environmental impacts more generally in a review article. These articles were published in the Journal of Cleaner Production and Rapid Prototyping Journal and claim these audiences accordingly: production engineers aiming for cleaner processes in RP or rapid manufacturing (RM).

Nearly all authors lamented the lack of research in this area: studies that would validate the claim that AM technologies are more environmentally benign than conventional manufacturing methods in terms of waste, energy, material use, emissions and so on. The study described in [27-RPJ] directly compared AM with mass production (MP) by determining the ‘crossover’ production volume at which it makes environmental sense to produce a part using selective laser sintering (SLS) rather than conventional injection moulding (IM): SLS was more energy efficient only with very small production volumes. However, as SLS also allows small batches at the same cost per piece and customization of each piece or batch to an extent that IM can never reach, one conundrum in researching the sustainability benefits of distributed production becomes apparent: the trade-off between high environmental impact per unit in small volumes and low impacts per unit but in mass quantities. This also entails the challenge to identify the most sensible comparison point and system boundaries. (Chin and Smithwick (2010) [5-MCPC] also attempt a comparison between mass customization and mass production using secondary data, discussed in Section 4.2.2.1.)

Three lab experiments highlighted how environmentally-oriented production planning is often concomitant with financial savings in electricity (i.e. [18-RPJ] and [13-JCP]) or material use (i.e. [9-RPJ]). A further study, [16-RPJ], experimented with recycled glass powder as a new material in 3D-Printing (3DP) technology.

The final paper in this category, [10-RPJ], was a review article on environmental issues and evaluation in AM. The authors focused particularly on health and safety, waste and energy, highlighting the health and environmental risks due to material toxicity that have not yet been identified (even at the time of writing this review, as confirmed in Huang et al., 2013). Aside from toxicity during use, the authors pointed to the disposal and post-processing stages as problematic because of the materials' unknown properties.

4.2.2. *Mass Customization and Personalization*

The second major category, Mass Customization and Personalization, is the largest. It has been divided into four sub-categories according to topic, audience and knowledge-building aim as regards sustainability (Table 3).

4.2.2.1. Sustainability of mass customization. Three papers discussed how to evaluate the sustainability of mass customization versus mass production by breaking down their stages. Chin and Smithwick (2010) [5-MCPC] and Petersen et al. (2011) [23-MCPC] both attempted to identify which MC stages are clearly more environmentally benign (or hold potential to be). Badurdeen et al. (2010) [1-MCPC] focused on the post-use stage, which they regarded as under-addressed, in a conceptual exploration on closing MC resource loops.

4.2.2.2. Frameworks and models. A sizable proportion of the papers reviewed put forth frameworks and tools for rethinking the mass customized offering, evaluating and improving its environmental footprint, and better understanding how to leverage MC characteristics to combined economic and environmental advantage. The model in Medini et al. (2011) [17-MCPC] aimed to map the MC enterprise's interrelationships with the external environments. Corti et al. (2011) [6-MCPC] proposed a “sustainable mass customized reference framework”, setting out the (interdependent) steps involved in product, production system and supply chain design. The framework in Nielsen et al. (2011) [19-MCPC] drew together eco-design principles and modular product architectures. Sakao et al. (2005) [24-MCPC] proposed that sustainability must be tackled earlier on in the design process if dematerialization is a goal, describing a tool aimed to help planners focus more on “customer value”. Souren (2003) [25-MCPC] addressed the end-of-life stage, presenting a discussion on the barriers to and enablers of closed loop MC processes in order to re-orient MC practice towards a “recovery economy”.

While the above frameworks involved qualitative descriptions, Wijekoon and Badurdeen (2011) [29-MCPC] and Letmathe (2003) [14-MCPC] suggested that quantifying factors offers managers better strategic tools for evaluation and application. In the former, the model incorporated a wide set of performance metrics for a sustainable MC business model. In the latter, eco-efficiency was translated into a costing method to tackle the challenges involved in ranking or weighting environmental impacts.

In sum, all papers in this section were geared to an operations management MC audience and all represented conceptual explorations with little or no testing reported. What was especially salient was the producer–consumer relationship in these representations of distributed production: these were clearly producer centric and only [24-MCPC] aimed to bring the sustainability analysis further upstream, before the product/service idea was even born. Closing resource loops was also a recurring concern, which will be discussed further in Section 4.3.

4.2.2.3. Product design. Another notably consistent theme of topical focus and audience connected papers *by* design researchers speaking mainly to an audience *of* product designers. This subcategory is nevertheless the most heterogeneous, encompassing journal articles and conference papers, empirical studies and propositional explorations. Distributed production for these authors was mainly understood as the ability to personalize products via digital production, but this was also heterogeneously explored: consumer input in these studies ranged from, for example, providing body measurements for bespoke fashion apparel to actually making or assembling garments themselves from kits or open source designs.

For Diegel et al. (2010) [8-JSD], in a conceptual article, environmental sustainability is better ensured when designers follow eco-design principles but also strive to create “*lasting* objects of desire, pleasure and *attachment*” [emphasis added]. For these authors additive manufacturing technologies enhance designers' expression and thus “design quality”, leading in turn to more pleasing products. AM is also highly suited to customizing products according to “customer needs” (which were unspecified here). This potentially leads to a greater attachment to the product which will therefore be used longer and not thrown away prematurely. This is described and emphasized here as a ‘formula’, as it was a recurring theme in this category as well as a cross-cutting theme among several categories (see Section 4.3.1).

Black and Eckert (2007) [3-MCPC] and Black et al. (2010) [4-MCPC] also focused on the design process, in a project description where the ultimate aim was to create fashion apparel that is more likely to be cherished and kept. Niinimäki (2010) [20-MCPC] likewise proposed that designers can effect person-product attachment and thereby product longevity but paid greater attention to the sociological and socio-cognitive understanding of this attachment (the “customer needs” that were unspecified above).

In this sense, [20-MCPC] saw beyond the technologies to the potential of the new practices or even business models afforded when designers (also) learn to engage with the consumer in new ways. Ballie and Delamore (2011) [2-MCPC] touted this new interaction as "co-creation", where "design experiences" matter as much as a well-designed garment in their conceptual exploratory paper. Niinimäki and Hassi (2011) [21-JCP] described these novel interactive fashion practices in more detail, discussing how the current unsustainable fashion industry can effect changes that are both environmentally beneficial and acceptable to consumers (according to survey results).

These design papers were thereby the most consumer oriented of all reviewed papers (and categories). Even so they did not neglect the production side, whether this entailed inclusion of eco-design considerations or touting the benefits of digital manufacturing technologies in promoting product longevity. Moreover, while the term *prosumer* was seldom used, the notion of new activities and business models that involve consumers/users in radical new ways arose as significant in this category.

4.2.2.4. Other. The final group in the Mass Customization category collects four studies that addressed other concerns or audiences than the three sub-categories above. For Steffen and Gros (2003) [26-MCPC], digital fabrication (of furniture) as local, distributed production was hypothesized to support sustained employment and regional development while avoiding transportation impacts. Fogliatto et al. (2012) [11-IJPE] presented a widely cited literature review on mass customization, where environmental implications were presented as a marginal but "promising" area of future research linked to "MC value".

For de Brito et al. (2008) [7-IJPE], examining attitudes in the fashion industry, customization was an emerging area of interest. However in this study customization and sustainability were not explicitly linked and were simply co-existing concerns for more sustainable supply chains. Finally, the only engineering-led study to adopt the term "prosumption" was Fox and Li (2012) [12-TFSC], whose framework for roadmapping material technologies was aimed especially at entrepreneurs and regional development authorities, to better determine what technologies support "sustainable" prosumption practices. A key issue for the authors was the localization of production and materials that corresponds with lower transport emissions. This issue will be further addressed in Section 4.3.3.

4.2.3. Fabbing

The third main category in this review is that of Fabbing, personal fabrication and peer-to-peer production employing digital fabrication equipment (Table 4). In two papers fabbing was an explicit facilitative component in more sustainable production and consumption patterns: in Manzini (2009) [15-DS] (as "distributed systems" of production) and Pearce et al. (2010) [22-JSD] (referring to 3D printing technologies and Fab Labs). In both papers fabbing or peer production was seen as a way to empower local communities and encourage responsible use of local resources (physical and social). In this sense, both papers (explicitly in the former, implicitly in the latter) sought to flag up the *resilience* that characterizes *distributed* networks. This association thus connected network agility with socio-ecological sustainability in a larger scale, in contrast to the simpler production agility supporting socio-economic sustainability more often implied in the previous sub-categories.

The third paper in this section, von der Gracht and Darkow (2010) [29-IJPE], addressed "fabbing" directly but did not explicitly espouse it as a route to less environmental impact. Rather the focus was on how (or if) fabbing will affect logistics, manufacturing and supply chains in part of a Delphi study. Fabbing was included as an unexpected or surprising scenario that, while unlikely, could "revolutionize production fundamentally", especially for "less complex consumer goods".

Section 4.2 has summarized the topical categories of the reviewed papers and especially drawn attention to how researchers have connected the distributed production practice – its specific characteristics as distinct from mass production – to its sustainability potential, whether this is tied to dematerialization potential of the technologies or reduced impacts due to localization. Moreover this potential may be embedded in the new relationship between producer and consumer (and the nature of the consumer 'input'), but it is mainly the design papers that examine this relationship among consumer, producer and product more profoundly. The following section will summarize the main umbrella themes that emerged from the analysis.

4.3. Cross-cutting themes

Subsequent to categorization, the analysis phase aimed to identify and collate salient cross-cutting themes that delved deeper into the research questions. These themes are listed in Table 5 in random order. The most compelling themes are described in this section, in terms of best representing the research material in this review but also highlighting key assumptions that deserve further scrutiny.

4.3.1. Product longevity

As seen in Section 4.2.2.3, a notable number of authors in this review were concerned with extending product life spans, suggesting how to combat psychological obsolescence by design via personalization.[7] For several other authors, the focus was less on the consumer and more on the producer: how end-of-life (EOL) can best be tackled in the mass customizer's business model and how personalization both enables and problematizes recovery.

Commonly mentioned issues were the difficulty to reuse individualized products, on the one hand, and the ability to incorporate disassembly in modular architectures on the other (e.g. in [6-MCPC]). [23-MCPC] discussed these enablers and barriers according to various EOL strategies such as remanufacturing or recycling. [25-MCPC] emphasized the importance of stronger communicative and "learning" relationships between consumer and producer in MC.

Use intensity was a related concern in several papers: [25-MCPC] pointed out how the sense of ownership of personalized products would problematize any product sharing or "eco leasing" solution that could better ensure higher use intensity. [14-MCPC] hypothesized that a product tailored to a consumer's needs will be used more, thereby decreasing the environmental impact "per service unit". The notion of Product-Service System (PSS), where the consumer is offered a function rather than a product in order to optimize resource use (Mont, 2002), was seen by several authors as a solution to these conundrums: a way to establish the business case for closing loops by personalizing the *customer satisfaction* rather than the product. PSS was mentioned as a design strategy in [21-JCP], as a business model where products are "value generating assets" in [1-MCPC] and as an operational model in [29-MCPC]'s evaluative framework.

In short, the authors seemed unsure of how to intensify the use of a personalized product if not through sharing, what exactly to customize in the product–service combination, and how to manage issues of ownership. On the one hand, PSS-oriented

[7] i.e. papers 3, 4, 8, 20, 21 and 26.

strategies can also draw attention to stakeholder relationships, novel combinations of actors to deliver satisfaction (Vezzoli et al., 2014), which may serve to meet circular economy goals. On the other hand, these studies remained mainly conceptual and untested; there is ample room for more research and practical interventions to test the hypotheses the authors raised. Empirical evidence validating our commonly held assumption that product attachment can have a positive effect on consumption patterns and material flow (i.e. absolute dematerialization) would also be beneficial.

4.3.2. Co-design

As stated throughout this review, the increasing ability of a consumer to influence what is produced is a key characteristic in the construct of distributed production. In a notable number of papers in this review, the term 'co-design' was used as shorthand to describe this interaction between consumer and producer[8] or between designers and non-designers.[9] However, the term was largely left undefined and under-explained, which was somewhat surprising.

This vagueness stimulated two further questions: first, what exactly is the nature of co-design envisioned by the authors? Secondly, who is responsible for initiating, designing, implementing and/or evaluating the co-design process in these contexts? As this is clearly an operational issue for mass customization practitioners, i.e. the "decoupling point", the review article [11-IJPE] provided more detail on how the MC field regards co-design, with research attention given especially to internet- and technology-enabled collaboration. Nevertheless the discussion seemed somewhat limited to a collection of "customer choices", and an MC research strand that uses "non-conventional technologies" to co-design with customers was described as "emerging".

In the MCPC conference papers it was mainly implied that the producer was in charge of co-design; likewise, in some of the design-centric papers, in [4-MCPC] and [26-MCPC], for instance, what is offered to the consumer remains the designers' choice. At the other end of the scale, in contrast, [15-DS]'s conception of co-design, while abstract and visionary, seemed to imply a greater allocation of agency among all parties.

A related and more relevant set of questions also arose from the papers' referencing to co-design: upon whom does the onus lie for environmental evaluation and decision-making, and how is this addressed in the conception of 'co-design'? Many of the conference papers focused on cleaner production strategies designed and implemented by the producer, i.e. the producers' responsibility. The consumers' input in 'co-design' was presented simply as 'needs', resulting in production of "only what truly adds value for customers" (as argued in [1-MCPC]). In some of the design-centric papers, it was not only the designers' responsibility to make eco-design decisions during the process but also to control the consumer's input and therefore even the definition of 'need'.

The authors in [1-MCPC], [17-MCPC] and [29-MCPC] attempted to take the discussion a step further, highlighting the need to incorporate eco-conscious choices in the product configurator or consider sustainability in the co-creation planning. This explicitly aimed not only to inform the consumer about e.g. environmental impacts in production and/or use, but also to allow both sustainability constraints *and* consumer need dictate *what* is actually produced as opposed to what is merely customized. In the journal papers, [21-JCP] described a wide range of co-design options, which in turn implied a variety of ways producers, designers and consumers can share both environmental information and responsible decision-making, including what is produced. In [15-DS] the whole purpose of 'co-design' was to co-create sustainable solutions and knowledge about them.

4.3.3. Local production

For all papers explicitly mentioning 'local' issues, the main sustainability benefit was avoidance of environmental impact related to transport. For the authors of [12-TFSC], local production was a success factor integral to the "expansion of prosumption". In [22-JSD], local materials and solutions to local needs, enabled by open source 3D printers, were important in the global South, where resources, skill bases and access to global supply chains are often limited.

However, further research on changing supply chains, for instance, would clarify if, how and when decentralizing production reduces negative environmental impact. [5-MCPC], for instance, pointed out that despite popular assumption, mass customization often occurs far from the customer in practice. Moreover the logistics experts surveyed in [28-IJPE] did not find it probable that the "decentralised production of many goods on-site in small-scale factories" would lead to significant structural changes for the logistics industry in 2025.

4.3.4. Technology affordances

The final cross-cutting theme was a category where authors aimed to capture the 'nature of the process' or what they believed to what ends a technology (or process or material) best lent itself, a category later called 'technology affordances'. Digital manufacturing was of particular interest to several authors with respect to what it affords, technically and materially, as well as environmentally.

For [12-TFSC], this was the core of their study: how material technologies promote particular production and consumption patterns. From the design point of view, [8-JSD] and [26-MCPC] focused on how designing for additive manufacturing differs from designing for mass production aesthetically and structurally. For these authors, the environmental benefits of designing and producing using AM technologies were clearly related to emotional attachment and product longevity. For the papers solely concerned with AM technologies, as described in Section 4.2.1, material saving was especially emphasized as an environmentally relevant benefit, while [10-RPJ] also highlighted the role of AM *prototyping* as a design tool to better ensure consumer acceptance and less waste.

The AM-centred papers revealed other compelling implicit and explicit issues. In [13-JCP]'s study of energy consumption, for instance, an optimal low energy density range for SLS was identified, which further offered the possibility to eliminate the preheating phase. The authors in [18-RPJ] drew attention to AM equipment design that in one case actually reduces manufacturing time, as the software identifies the longest diagonal and starts at that point. This led to reduced electricity consumption. In [9-RPJ], the authors pointed out that manufacturers' specifications for powder use are generally followed in the industry but tend to lead to unnecessary waste. The authors did not discuss the implications further, but one could put forward that AM equipment manufacturers themselves could pursue research and development of technologies that enable their users to operationalize more environmentally responsible practices.

4.4. Synthesis

To further synthesize the findings discussed in the previous sections, a concept map (Hart, 1998) was created (Fig. 4). It is important to note that the map is proposed as a tool for locating

[8] i.e. in papers 1, 6, 11, 17, 21, 26, 29.

[9] In papers 2, 4, 15.

current and emerging distributed production activities *and* research, where the quadrants are not viewed as having clear borders but rather as a continuum. Further research can serve to validate the axes chosen or evolve them as circumstances change.

4.4.1. The distributed production landscape

The two extremes of the construct 'distributed production' most discussed in the literature, and most visible in current real-life activities, were placed in the bottom left and top right quadrants (Fig. 4). As a reminder that distributed production activities are both commercial and conducted for non-economic reasons, the labels 'market influence' and 'non-market influence' were inserted at the two extremes. At bottom left, therefore, representing activities nearest the current dominant mass production paradigm, 'mass customization' at its extreme aims to retain control over consumer input (i.e. the producer retains the final decision on what is personalized and how, likely for cost and market reasons). Personalization is therefore 'batch' and modular rather than unique and volumes are relatively large. The papers in this review discussing mass customization were placed in this quadrant.

At top right, in 'personal fabrication' an individual produces her own artefacts (e.g. in a Fab Lab or 'maker space'). She has full agency and authority over both design and fabrication, which depends only on her own competence. Scales are small: facilities, volumes and equipment. It is assumed the authors in the Delphi study, [28-IJPE], had this conception of 'fabbing' in mind and aimed to elicit from the experts how likely this would spread, e.g. shift towards the bottom right quadrant.

The top left and bottom right quadrants were less obviously represented in the reviewed literature and, to the researcher's knowledge, see less representation in real-life activities. They have therefore been accorded working titles and descriptions based on their positions on the axes. In the bottom right, we must imagine personal fabrication on a larger scale ('mass fabrication'), likely the material version of Web 2.0 peer content development and sharing visible today. The emphasis remains on the individual's authority over what is designed and made (i.e. a truly peer-to-peer arrangement). This accords with the conceptions of distributed production proposed in [15-DS] and [22-JSD], and, given the variability in consumer input in the design services described in [21-JCP], it is placed in the middle of the scale.

In the top left quadrant, the scale is 'small' and therefore the level of personalization can result in one-offs and bespoke services. Nevertheless the producer retains authority over what is produced and what consumer input is needed. This conception of 'bespoke fabrication' is influenced by the vision of prosumption presented in [12-TFSC], and the authors' conception of "neo-craft" "technofacture" proposed in [25-MCPC] may also be placed here.

4.4.2. The environmental sustainability of distributed production

The final synthesis task returned to the question of how the authors see the relationship between distributed production and environmental impact, superimposing the opportunities onto the previous 'landscape' (Fig. 5). Beginning in the 'mass customization' quadrant, the authors reviewed saw the main environmental benefits as the capacity to avoid the pre-consumer waste seen in mass production (especially in the fashion and clothing industry), to enable recovery and create closed-loop systems, and to incorporate sustainability-led parameters in the product configurators. They also saw these benefits as conditional upon the ability to exploit the stronger consumer–producer relationships and modularity in MC models.

In comparison, the authors envisioning a more 'bespoke fabrication' construct tended to emphasize how 'small' means 'local' and therefore fewer emissions and impacts from transport. Bespoke products were also assumed to entail less overall material and energy use as they would be used longer and/or more intensively and be less vulnerable to mechanisms of technical, aesthetic, functional and/or psychological obsolescence. However, many authors highlighted the need for high quality to ensure pleasurable associations and therefore attachment as well as functional longevity.

In 'personal fabrication' in the top right, authors also emphasized the benefits of localizing both production and materials. Research in rapid prototyping confirms that a fabbed artefact may have relatively high environmental impacts per unit, but at this personal scale overall volumes remain very low. When the scale is increased in the 'mass fabrication' construct, in the bottom right,

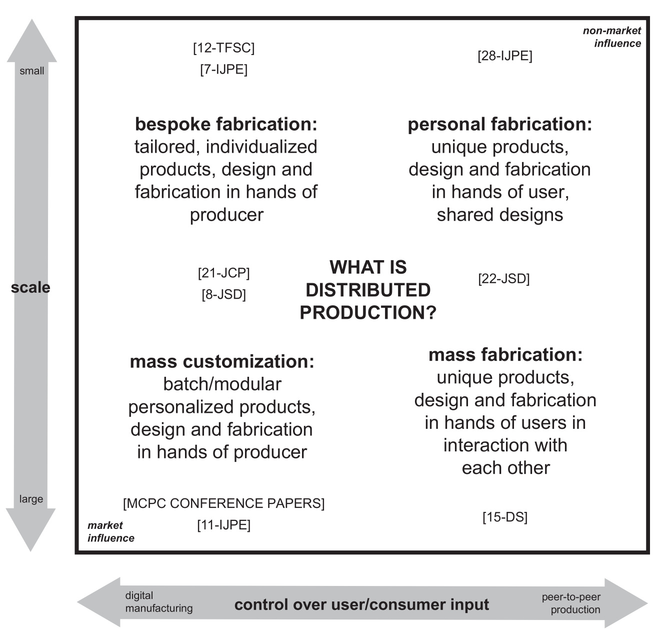

Fig. 4. Conceptualizing the distributed production landscape.

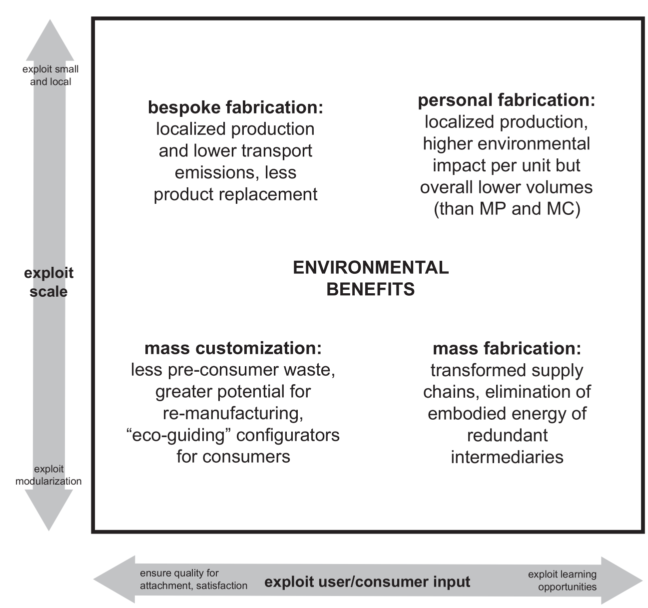

Fig. 5. Opportunities to promote environmental sustainability in distributed production: summary of the authors' propositions.

Please cite this article in press as: Kohtala, C., Addressing sustainability in research on distributed production: an integrated literature review, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.09.039

Table 1
Key to articles and source abbreviations.

No.	Article	Journal/Conference	Reference
1	[1-MCPC]	World Conference on Mass Customization and Personalization (MCPC)	Badurdeen et al., 2010
2	[2-MCPC]	MCPC	Ballie and Delamore, 2011
3	[3-MCPC]	MCPC	Black and Eckert, 2007
4	[4-MCPC]	MCPC	Black et al., 2010
5	[5-MCPC]	MCPC	Chin and Smithwick, 2010
6	[6-MCPC]	MCPC	Corti et al., 2011
7	[7-IJPE]	International Journal of Production Economics (IJPE)	de Brito et al., 2008
8	[8-JSD]	Journal of Sustainable Development (JSD)	Diegel et al., 2010
9	[9-RPJ]	Rapid Prototyping Journal (RPJ)	Dotchev and Yusoff, 2009
10	[10-RPJ]	RPJ	Drizo and Pegna, 2006
11	[11-IJPE]	IJPE	Fogliatto et al., 2012
12	[12-TFSC]	Technological Forecasting and Social Change (TFSC)	Fox and Li, 2012
13	[13-JCP]	Journal of Cleaner Production (JCP)	Franco et al., 2010
14	[14-MCPC]	MCPC	Letmathe, 2003
15	[15-DS]	Design Studies (DS)	Manzini, 2009
16	[16-RPJ]	RPJ	Marchelli et al., 2011
17	[17-MCPC]	MCPC	Medini et al., 2011
18	[18-RPJ]	RPJ	Mognol et al., 2006
19	[19-MCPC]	MCPC	Nielsen et al., 2011
20	[20-MCPC]	MCPC	Niinimäki, 2010
21	[21-JCP]	JCP	Niinimäki and Hassi, 2011
22	[22-JSD]	JSD	Pearce et al., 2010
23	[23-MCPC]	MCPC	Petersen et al., 2011
24	[24-MCPC]	MCPC	Sakao et al., 2005
25	[25-MCPC]	MCPC	Souren, 2003
26	[26-MCPC]	MCPC	Steffen and Gros, 2003
27	[27-RPJ]	RPJ	Telenko and Seepersad, 2012
28	[28-IJPE]	IJPE	von der Gracht and Darkow, 2010
29	[29-MCPC]	MCPC	Wijekoon and Badurdeen, 2011

we imagine that supply chains may be transformed and movement of materials and components more prevalent than finished consumer products (as suggested in [28-IJPE]). Some authors (especially [5-MCPC]) highlighted the embodied energy in retail and other infrastructure that would not be expended in these changed distribution arrangements. With regard to how consumer involvement can influence the environmental impact of peer production (i.e. the horizontal axis), the papers reviewed rather abstractly referred to the indirect environmental benefits of knowledge and capacity building.

5. Discussion

Discussing the implications of this study must take into account the two objectives of the review. The first is to map the landscape of research, i.e. who is discussing distributed production and who is not (research questions 1 and 3), and the second, its contents: if distributed production can enable the dematerialization of consumption (research question 2).

5.1. Hypotheses on environmental benefits

The first contribution of this paper is the summary of distributed production as seen in Figs. 4 and 5: what distributed production entails, and why and how these activities are seen to lead to more sustainable socio-economic patterns. The patterns found in this study mainly emphasized production only according to need, stronger person-product affinities and significant connections between producer and consumer.

However, that many studies have remained conceptual (and – among this group – often seemed to remain as conference papers and not turned into full journal papers) is currently a hindrance to an evidence-based view of the phenomenon. There is need for more empirical data, and from more fields than design and engineering.

Because the reviewed papers have come forth from mainly the engineering and production planning professions, this has created a rather one-sided view on the consumer–producer relationship that seems to stress only communications. As more laypeople gain access to manufacturing technologies, however, this relationship is becoming more complex. The true value of ‘co-design’ needs to be further unpacked in both research and practice, as it appears to be a key factor differentiating distributed production from the mass production mode. One-sided ‘cleaner production’ is not enough: production and consumption must be evaluated together. A strategy of cleaner prosumption reconsiders not only *how* something is produced, but *what* is produced (or prosumed) and why.

There is hence need for discussion on the valuing systems behind distributed production activities involving material goods. This would serve practical, operational objectives and clarify the axiological underpinnings. Many disciplinary and epistemic

Table 2
Summary of Additive Manufacturing Processes category.

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Energy	[13-JCP]	Rapid Prototyping (RP) technologies for prototyping: Selective Laser Sintering (SLS)	Theoretical optimal process energy measurement	Energy consumption of production optimizing dimensional accuracy	Operations and production management
	[18-RPJ]	RP technologies in manufacturing parts: SLS and 3D Printing (3DP)	ISO 14000 as an example	Reducing electricity consumption	Operations and production management
	[27-RPJ]	Additive Manufacturing (AM) technologies (SLS) in manufacturing parts	Life Cycle Inventories (LCI), comparing AM with mass production (injection moulding)	Energy consumption of production	Operations and production management
Recycling	[9-RPJ]	RP technologies (SLS) for prototyping with potential for manufacturing (RM)	Material management and recycling	Cost savings, quality assurance prioritized but environmental implications if RM expands	Operations and production management
	[16-RPJ]	RM technologies for producing objects/parts: 3DP	Recycled glass powder experimentation	Recycled glass for “sustainable future for 3DP”	Operations and production management
Environmental impacts	[10-RPJ]	RP and Rapid Tooling (RT) for prototyping and enabling Mass Customization (MC)	Industrial Ecology (IE), Environmental impact assessment (EIA), Life Cycle Assessment (LCA)	RP materials, especially toxicity	Operations and production management

Please cite this article in press as: Kohtala, C., Addressing sustainability in research on distributed production: an integrated literature review, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.09.039

Table 3
Summary of Mass Customization and Personalization category.

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Sustainability of MC	[1-MCPC]	Mass Customization (MC)	Triple Bottom Line, '6Rs' approach, Sustainable Supply Chain Management	Product-Service System (PSS) to enable closed loops	Operations and production management
	[5-MCPC]	MC	Life cycle analysis of energy and material use	Embodied energy analysis in MC compared to mass production (MP)	Operations and production management
	[23-MCPC]	MC	End-of-Life strategies, eco-design, life cycle thinking	MC sustainability gains compared to MP	Operations and production management
Frameworks and models	[6-MCPC]	MC	Sustainable MC criteria (product architecture, manufacturing, supply chain)	MC as route to (environmental) sustainability through e.g. less waste and inventory	Operations and production management, Design and engineering
	[14-MCPC]	MC	Eco-efficiency and eco-effectiveness, "CML concept"	Eco-Efficiency through efficiency costing	Operations and production management, Environmental management
	[17-MCPC]	MC	Social, economic, environmental dimensions in enterprise assessment; stakeholder assessment	Enterprise interrelationships (with society and environment)	Operations and production management
	[19-MCPC]	Mass Customization, Personalization and Co-creation (MCPC)	'Ten Golden Rules of Eco-Design'	Sustainability through modularization	Operations and production management, Design and engineering
	[24-MCPC]	MC	Service Engineering tool to ensure customer satisfaction and in turn dematerialization of products	Value creation and customization through customer satisfaction	Operations and production management, Design and engineering
	[25-MCPC]	Mass Customization and Personalization (MCP)	"Double layer closed loop model"	Recovery and closed loop opportunities and barriers in MCP	Operations and production management, Environmental management, Design and engineering
	[29-MCPC]	MC	6R methodology, PSS design approaches to promote dematerialization	Modelling framework to evaluate product and PSS configurations	Operations and production management, Design and engineering
Product design (fashion)	[2-MCPC]	"Co-creation", "user-based tools for discovery, creation, production and sharing"	Design approaches such as "emotionally durable design", "co-design", "open source design"	Strengthening relationship between fashion designer and customer to reduce e.g. waste	Design and engineering
	[3-MCPC]	Personalization and customization through (in part) rapid prototyping technologies	"Considerate Design Footprint" to assess costs and risks including environmental impacts	Considering environmental impacts in product design stage	Design and engineering
	[4-MCPC]	Personalization through (in part) rapid prototyping technologies	Personalized fashion to ensure fit and comfort and in turn extended use	Reducing product replacement, consumption via engagement and empathy	Design and engineering
Product design (textiles)	[20-MCPC]	Customizing via digital (textile) technologies	Product longevity via uniqueness	Fostering product-person attachment	Design and engineering
Product design (clothing and textiles)	[21-JCP]	MC, "co-creation", halfway products	Business models that focus on user satisfaction and outcomes	Design strategies to extend product life span	Design and engineering

Product design	[8-JSD]	MC with the help of Additive Manufacturing (AM)	MC product design and AM manufacture to create "objects of desire"	Product longevity via "design quality"	Design and engineering
Other studies	[7-IJPE]	Customized (apparel), personalized value	Sustainable supply chains and logistics, understanding benefits and barriers	Industry viewpoints where customizing is one small (competitive) aspect	Operations and production management
	[11-IJPE]	Mass Customization (MC)	Environmental implications of MC: likely to influence "dissemination and acceptance of MC technologies and methods"	Environmental and ethical issues as recent but marginal focus of study in literature, linked to value dimensions	Operations and production management
	[12-TFSC]	"Prosumption", customer "authority" over design and production	Prosumption as desirable new paradigm, framework to roadmap (sustainable) material technologies	Point-of-demand production, avoiding transportation impacts	Regional development, Design and engineering
	[26-MCPC]	MC and "art customization", decentralized production	Meeting ecological demands via sustainable regional development	New forms of furniture production bridging craft skills and digital technologies	Regional development, Design and engineering

Table 4
Summary of Fabbing category.

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Peer-to-peer	[15-DS]	Distributed systems, "sustainable distributed knowledge economy"	Design for sustainability that facilitates social learning process towards sustainable society	Agenda for design research to promote co-creation of sustainable solutions	Design and engineering
	[22-JSD]	Open source 3D printers as Open Source Appropriate Technology (OSAT)	Sustainable development especially poverty alleviation via appropriate technologies for local village empowerment	Open source 3D printers' characteristics and optimum future development	Design and engineering, International development
Logistics	[28-IJPE]	Fabbing in small-scale factories or at home	Environmental sustainability not connected directly to fabbing but as umbrella concern for logistics	Fabbing as a wildcard that may impact logistics, environmental impacts implicit	Operations and production management

Table 5
Salient concerns in reviewed papers.

	[1-MCPC]	[2-MCPC]	[3-MCPC]	[4-MCPC]	[5-MCPC]	[6-MCPC]	[7-IJPE]	[8-JSD]	[9-RPJ]	[10-RPJ]	[11-IJPE]	[12-TFSC]	[13-JCP]	[14-MCPC]	[15-DS]	[16-RPJ]	[17-MCPC]	[18-RPJ]	[19-MCPC]	[20-MCPC]	[21-JCP]	[22-JSD]	[23-MCPC]	[24-MCPC]	[25-MCPC]	[26-MCPC]	[27-RPJ]	[28-IJPE]	[29-MCPC]
longevity		×	×	×	×	×		×						×						×	×		×		×	×			×
co-design	×	×		×		×					×				×		×				×					×			×
design	×	×	×	×		×		×		×					×				×	×	×	×		×	×	×		×	
local		×	×	×	×							×			×					×		×	×			×		×	
PSS	×																				×								×
end of life/reuse/recovery	×				×	×			×	×				×					×			×	×		×				×
open source		×													×	×					×	×							
craft		×	×	×								×			×					×						×			
'developing' countries							×					×										×							
Network/Knowledge Society												×			×													×	
time		×			×										×					×									
future												×			×			×		×		×				×		×	
technology affordances			×	×	×			×	×	×		×	×		×	×		×			×	×				×	×	×	

perspectives, from economics and marketing to management science and organizational behaviour, may contribute to this knowledge building.

5.2. Unknown consequences

There were also environmental implications arising from the reviewed papers and their synthesis that were not discussed by the authors. Because of the heavy emphasis on frameworks and identifying environmental benefits, combined with the lack of, for instance, real-life case studies, the environmental harms (potentially) concomitant with a decentralized production paradigm remained unacknowledged. This realization resulted in the creation of a further 'landscape' of environmental concerns to supplement the previous two (Fig. 6), and the second contribution of this paper.

Firstly, the more personal fabrication becomes (i.e. the further right in the map), the more exposed the individual becomes to materials and processes and their as yet unknown properties such as toxicity. This also means it is less certain that other safety mechanisms are in place (as they would be in more established and regulated contexts such as commercial activities). The risk of harmful emissions to the environment may also be greater.

The fabrication of new types of products may additionally render them less amenable to existing consumer recycling systems, e.g. for plastics, whether because of actual material properties or barriers due to changed habits and routines. Moreover, even if some consumer products are replaced by materials in new distribution arrangements and environmental impacts associated with the retail infrastructure lessen, it is possible the production, storage and distribution of materials and components (and their inherent impacts) remain just as invisible to the consumer as the current mass production supply chain is.

On the left side of the landscape, the reviewed papers had raised the concern of reusing and recycling customized products. There are also several unstated implications: for instance it remains unclear if the high quality production needed to better ensure product longevity will involve more resources and energy that will ultimately counteract the environmental gains from longer or more

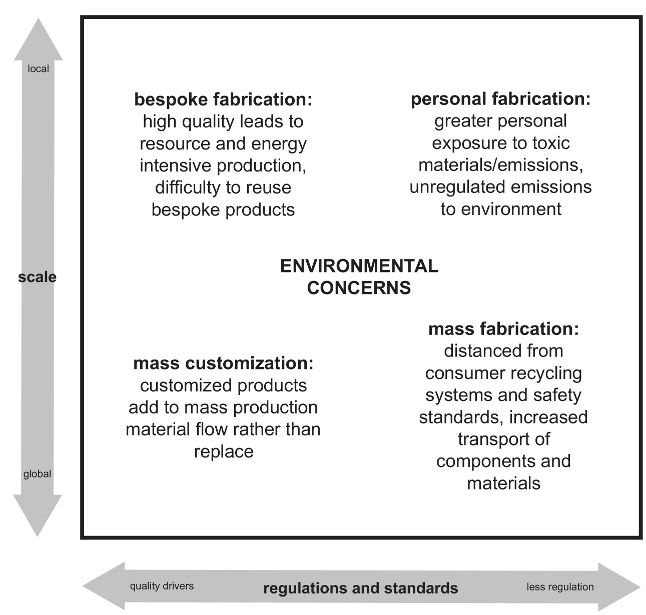

Fig. 6. Threats to environmental sustainability in distributed production (arising from but mainly not explicit in the reviewed papers).

intense product use. It is also debatable whether mass customization will replace some mass production material flow or simply add to it, not to mention the growing environmental footprint of the internet and information and communications technologies. Further observation and analysis may be able to determine how these activities play out in time – and what time and scale settings are most appropriate for study.

6. Conclusions

Distributed production holds promise of greater environmental sustainability, but it is not a given that it will be a new, clearly cleaner production paradigm. The review illuminated the opportunities for greater environmental sustainability as well as potential threats, addressing of which could serve to improve these novel, emerging practices today. The concept maps presented in the review summarize the reviewed papers' positions on environmental benefits and may also provide clues to how distributed production may be defined and delimited as more research emerges.

This study has clarified what characterizes distributed production in its different forms, what is already known or hypothesized regarding its dematerialization potential, and what topics are fruitful arenas for further examination. The conceptualization can inspire and legitimize practitioners' experiments with business models, new customer–producer relationships and novel, reconfigured prosumption networks. By flagging areas where undesired environmental impacts may arise, the review guides further research and encourages practitioners to take them into account in their current and future activities.

Acknowledgements

We are grateful to Tiina Härkäsalmi, Sampsa Hyysalo and Frank Steiner for suggestions on previous drafts and we thank the editor and anonymous reviewers for their helpful comments on our manuscript.

Appendix A. Summary of sources: journals

Journal NAME, Dates	Total articles	Relevant	Focus (Journal's description)	Category (Journal's description)	Eigenfactor Category
Co-Design, 1(1) 2002–8(4) 2012	about 130	0	Research on nature of collaborative design from any design domain.	Collaborative Design, Design, Engineering and Technology.	n/a
Design Studies, 23(1) 2002 –33(6) 2012	about 330	1	Design activity, from cognition and methodology to values and philosophy.	Design Research in Engineering, Architecture, Products and Systems.	Robotics.
Ecological Economics, 40(1) 2002–84 2012	about 2240	0	Transdisciplinary. Management of ecology and economics. Commentaries, surveys, analyses, methodologies, ideological options.	Environmental sciences. Environmental Technology, Policy and Management, etc.	Economics.
International Journal of Production Economics 75(1 –2) 2002–140(2) 2012	about 2570	3	Multidisciplinary. Interface between engineering and management; academic approach and industrial applications.	Manufacturing and process industries, production.	Operations research.
Journal of Cleaner Production, 10(1) 2002–37 2012	about 1880	2	Interdisciplinary. Techniques, concepts and policies.	Industrial applications and Environmental Management, Legislation and Policy, Education.	Environmental Chemistry and Microbiology.
Journal of Consumer Culture, 2(1) 2002–12(3) 2012	about 160	0	Multidisciplinary. Theory and empirical.	Consumption and consumer culture. Sociology. Cultural Studies.	Sociology.
Journal of Industrial Ecology, 6(1) 2002–16(6) 2012	about 530	0	Interdisciplinary. Conceptual contributions, findings from primary research and practice.	'Industrial metabolism', 'industrial symbiosis'.	Environmental Chemistry and Microbiology.
Journal of Sustainable Development, 1(1) 2008–5(12) 2012	about 560	2	Transdisciplinary. Original research and reviews.	Environmental science, technologies, economics and policy; ecology; sustainable development.	na
Rapid Prototyping Journal, 8(1) 2002–18(6) 2012	about 415	5	Developments and applications in additive manufacturing (AM).	Mechanical and Materials Engineering.	Physics and Chemistry.
Technological Forecasting and Social Change, 69(1) 2002 –79(9) 2012	about 910	1	Multidisciplinary. Methodology and practice of technological foresight.	Technological Forecasting, Futures Studies.	Management Studies.

Appendix B. Summary of sources: conferences

Conference name	Conference description, focus year	Relevant (available full paper)	No. of sessions total	Sustain-ability sessions	No. of papers/ presentations total (in proceedings)	Sustainability papers /presentations
Additive Manufacturing Conferences	Industrialists and academics: Engineers, innovators, designers, business managers, academics and researchers, and AM materials and system developers. 'Exceptional papers' accepted.					
	2006	0	–	–	18	0
	2007	0	–	–	15	0
	2008	0	–	–	14	1
	2009	0	7	0	14	0
	2010	0	7	1	14	2
	2011	0	7	0	14	0
	2012	0	7	0	14	0
MCPC Conferences: International Conference on Mass Customization & Personalization	Interdisciplinary, scientists and practitioners. Innovation and research. Technological IT infrastructures, design applications, success stories and business models. Peer reviewed papers.					
	2003	3	14	1	117	4
	2005	1	31	0	124	4
"Extreme Customization"	2007	1	54	0	160	4
"Mass Matching: Customization, Configuration & Creativity"	2009 (Proceedings 2010)	4	29	2	95	11
"Bridging Mass Customization and Open Innovation"	2011	6	41	3	144	13
PINC Conferences: Participatory Innovation Conference	A spread in disciplines to cover innovation from several perspectives, including design, anthropology, conversation analysis, business, management, and public procurement. Peer-reviewed papers.					
	2011	0	5	0	68	2

References

Anderson, C., 2012. Makers: the New Industrial Revolution. Random House Business Books, New York, NY.

ATKINS Project, 2007. Manufacturing a Low Carbon Footprint: Zero Emission Enterprise Feasibility Study (Project No: N0012J). Loughborough University.

Badurdeen, F., Liyanage, J.P., Gupta, S., 2010. Product lifecycle-based approach to mass customization for sustainable manufacturing. In: Suominen, J., Piller, F., Ruohonen, M., Tseng, M., Jacobson, S. (Eds.), Proceedings of the 5th International Conference on Mass Customization & Personalization MCPC 2009. Aalto University School of Art and Design, Helsinki. Publication Series B 102, Presented at the Mass Matching – Customization, Configuration & Creativity Conference, October 4–8 2009, Helsinki, Finland.

Ballie, J., Delamore, P., 2011. E-Co-Creation for fashion: a review of co-creation and open innovation methods for sustainable fashion. In: Proceedings of the MCPC 2011 Conference. Bridging Mass Customization & Open Innovation, San Francisco, CA. Presented at the 2011 World Conference on Mass Customization, Personalization, and Co-creation.

Baran, P., 1964. On Distributed Communications: I. Introduction to Distributed Communications Networks (Rand Memorandum No. RM-3420-PR). RAND Corporation, Santa Monica, CA.

Bauwens, M., Mendoza, N., Iacomella, F., 2012. A Synthetic Overview of the Collaborative Economy. Orange Labs and P2P Foundation.

Benkler, Y., 2006. The Wealth of Networks: How Social Production Transforms Markets and Freedom. Yale University Press, New Haven, CA.

Black, S., Delamore, P., Eckert, C., Geesin, F., Watkins, P., Harkin, S., 2010. Considerate Design for Personalised Fashion: towards sustainable fashion design and consumption. In: Suominen, J., Piller, F., Ruohonen, M., Tseng, M., Jacobson, S. (Eds.), Proceedings of the 5th International Conference on Mass Customization & Personalization MCPC 2009. Aalto University School of Art and Design, Helsinki. Publication Series B 102, Presented at the Mass Matching – Customization, Configuration & Creativity Conference, October 4–8 2009, Helsinki, Finland.

Black, S., Eckert, C., 2007. Developing considerate design: Meeting individual fashion and clothing needs within a framework of sustainability. In: Mitchell, W.J., Piller, F.T., Tseng, M., Chin, R., McClanahan, B.L. (Eds.), Proceedings of the MCPC 2007 World Conference on Mass Customization & Personalization. Massachusetts Institute of Technology. Extreme Customization, Presented at the MCPC 2007 Conference, October 7–9 2007.

Bruccoleri, M., Nigro, G.L., Perrone, G., Renna, P., Noto La Diega, S., 2005. Production planning in reconfigurable enterprises and reconfigurable production systems. CIRP Ann. – Manuf. Technol. 54, 433–436.

Chin, R., Smithwick, D., 2010. Environmental impacts of utilizing mass customization: energy and material use of mass customization vs. Mass production. In: Suominen, J., Piller, F., Ruohonen, M., Tseng, M., Jacobson, S. (Eds.), Proceedings of the 5th International Conference on Mass Customization & Personalization MCPC 2009, Presented at the Mass Matching – Customization, Configuration & Creativity Conference, October 4-8 2009, Helsinki, Finland. Aalto University School of Art and Design, Helsinki. Publication Series B 102.

Corti, D., Taisch, M., Pourabdollahian, G., Bettoni, A., Pedrazzoli, P., Canetta, L., 2011. Proposal of a reference framework to integrate sustainability and mass customization in a production paradigm. In: Piller, F.T., Chesbrough, H. (Eds.), Proceedings of the MCPC 2011 Conference. Bridging Mass Customization & Open Innovation, San Francisco, CA. Presented at the 2011 World Conference on Mass Customization, Personalization, and Co-creation.

de Brito, M.P., Carbone, V., Blanquart, C.M., 2008. Towards a sustainable fashion retail supply chain in Europe: organisation and performance. Int. J. Prod. Econ. 114, 534–553.

Diegel, O., Singamneni, S., Reay, S., Withell, A., 2010. Tools for sustainable product design: additive manufacturing. J. Sustain. Dev. 3, 68–75.

Dotchev, K., Yusoff, W., 2009. Recycling of polyamide 12 based powders in the laser sintering process. Rapid Prototyp. J. 15, 192–203.

Drizo, A., Pegna, J., 2006. Environmental impacts of rapid prototyping: an overview of research to date. Rapid Prototyp. J. 12, 64–71.

Fogliatto, F.S., da Silveira, G.J.C., Borenstein, D., 2012. The mass customization decade: an updated review of the literature. Int. J. Prod. Econ. 138, 14–25.

Fox, S., Li, L., 2012. Expanding the scope of prosumption: a framework for analysing potential contributions from advances in materials technologies. Technol. Forecast. Soc. Change 79, 721–733.

Franco, A., Lanzetta, M., Romoli, L., 2010. Experimental analysis of selective laser sintering of polyamide powders: an energy perspective. J. Clean. Prod. 18, 1722–1730.

Gauntlett, D., 2013. Making Is Connecting: the Social Meaning of Creativity, from DIY and Knitting to YouTube and Web 2.0. John Wiley & Sons, Hoboken, NJ.
Gershenfeld, N., 2005. FAB: the Coming Revolution on Your Desktop – from Personal Computers to Personal Fabrication. Basic Books, New York.
Hart, C., 1998. Doing a Literature Review: Releasing the Social Science Research Imagination. Sage Publications, London, UK.
Hatch, M., 2013. The Maker Movement Manifesto: Rules for Innovation in the New World of Crafters, Hackers, and Tinkerers. McGraw-Hill Professional, New York, NY.
Huang, S.H., Liu, P., Mokasdar, A., Hou, L., 2013. Additive manufacturing and its societal impact: a literature review. Int. J. Adv. Manuf. Technol. 67, 1191–1203.
Jiang, K., Lee, H.L., Seifert, R.W., 2006. Satisfying customer preferences via mass customization and mass production. IIE Trans. 38, 25–38.
Johansson, A., Kisch, P., Mirata, M., 2005. Distributed economies – a new engine for innovation. J. Clean. Prod. 13, 971–979.
Kumar, A., 2007. From mass customization to mass personalization: a strategic transformation. Int. J. Flex. Manuf. Syst. 19, 533–547.
Leitão, P., 2009. Agent-based distributed manufacturing control: a state-of-the-art survey. Eng. Appl. Artif. Intel. 22, 979–991.
Letmathe, P., 2003. Quantifying the Eco-Efficiency of MCP. Presented at MCPC03: the 2nd International Conference on Mass Customization and Personalization, October 6–8 2003, Munich, Germany.
Manzini, E., 2009. New design knowledge. Des. Stud. 30, 4–12.
Marchelli, G., Prabhakar, R., Storti, D., Ganter, M., 2011. The guide to glass 3D printing: developments, methods, diagnostics and results. Rapid Prototyp. J. 17, 187–194.
Marsh, P., 2012. The New Industrial Revolution: Consumers, Globalization and the End of Mass Production. Yale University Press, New Haven, CA.
Medini, K., Da-Cunha, C., Bernard, A., 2011. Towards an integrated mass customization and sustainability assessment framework. In: Chesbrough, H., Piller, F.T. (Eds.), Proceedings of the MCPC 2011 Conference. Presented at the 2011 World Conference on Mass Customization, Personalization, and Co-creation: Bridging Mass Customization & Open Innovation, San Francisco, CA.
Mognol, P., Lepicart, D., Perry, N., 2006. Rapid prototyping: energy and environment in the spotlight. Rapid Prototyp. J. 12, 26–34.
Mont, O., 2002. Clarifying the concept of product-service system. J. Clean. Prod. 10, 237–245.
Moore, P., Karatzogianni, A., 2009. Parallel visions of peer production. Cap. Cl. 33, 7–11.
Nielsen, K., Jørgensen, K.A., Taps, S.B., Petersen, T.D., 2011. Supporting sustainability and personalization with product architecture. In: Chesbrough, H., Piller, F.T. (Eds.), Proceedings of the MCPC 2011 Conference. Presented at the 2011 World Conference on Mass Customization, Personalization, and Co-creation: Bridging Mass Customization & Open Innovation, San Francisco, CA.
Niinimäki, K., 2010. Developing sustainable products by deepening consumers' product attachment through customizing. In: Suominen, J., Piller, F., Ruohonen, M., Tseng, M., Jacobson, S. (Eds.), Proceedings of the 5th International Conference on Mass Customization & Personalization MCPC 2009. Aalto University School of Art and Design, Helsinki. Publication Series B 102, Presented at the Mass Matching – Customization, Configuration & Creativity, October 4-8, 2009, Helsinki, Finland.
Niinimäki, K., Hassi, L., 2011. Emerging design strategies in sustainable production and consumption of textiles and clothing. J. Clean. Prod. 19, 1779–1908.
Pearce, J.M., Blair, C.M., Laciak, K.J., Andrews, R., Nosrat, A., Zelenika-Zovko, I., 2010. 3D printing of open source appropriate technologies for self-directed sustainable development. J. Sustain. Dev. 3, 17–29.
Petersen, T.D., Jørgensen, K.A., Nielsen, K., Taps, S., 2011. Is mass customization sustainable? In: Chesbrough, H., Piller, F.T. (Eds.), Proceedings of the MCPC 2011 Conference. Presented at the 2011 World Conference on Mass Customization, Personalization, and Co-creation: Bridging Mass Customization & Open Innovation, San Francisco, CA.
Piller, F.T., Moeslein, K., Stotko, C.M., 2004. Does mass customization pay? an economic approach to evaluate customer integration. Prod. Plan. Control 15, 435–444.
Piller, F.T., Tseng, M.M. (Eds.), 2009. Handbook of Research in Mass Customization and Personalization. World Scientific, Singapore.
Poler, R., Carneiro, L.M., Jasinski, T., Zolghadri, M., Pedrazzoli, P. (Eds.), 2012. Intelligent Non-hierarchical Manufacturing Networks. Wiley, Hoboken, NJ.
Ritzer, G., Dean, P., Jurgenson, N., 2012. The coming of age of the prosumer. Am. Behav. Sci. 56, 379–398.
Ritzer, G., Jurgenson, N., 2010. Production, Consumption, Prosumption: the nature of capitalism in the age of the digital “prosumer”. J. Consum. Cult. 10, 13–36.
Rosvall, M., Bergstrom, C.T., 2011. Multilevel compression of random walks on networks reveals hierarchical organization in large integrated systems. PLoS ONE 6, e18209.
Sakao, T., Shimomura, Y., Comstock, M., Sundin, E., 2005. Service Engineering for Value Customization. Presented at the 3rd International Conference on Mass Customization and Personalization, September 18-21 2005, Hong Kong.
Souren, R., 2003. The Relevance of Recovery Economy to Mass Customization and Personalization. Presented at MCPC03: the 2nd International Conference on Mass Customization and Personalization, October 6-8 2003, Munich, Germany.
Steffen, D., Gros, J., 2003. Technofactory versus Mini-Plants: Potentials for a Decentralized Sustainable Furniture Production. Presented at MCPC03: the 2nd International Conference on Mass Customization and Personalization, October 6–8 2003, Munich, Germany.
Telenko, C., Seepersad, C.C., 2012. A comparison of the energy efficiency of selective laser sintering and injection molding of nylon parts. Rapid Prototyp. J. 18, 472–481.
Toffler, A., 1980. The Third Wave. Morrow, New York.
Torraco, R.J., 2005. Writing integrative literature reviews: guidelines and examples. Hum. Resour. Dev. Rev. 4, 356–367.
Troxler, P., 2013. Making the third industrial revolution: the struggle for polycentric structures and a new peer-production commons in the FabLab community. In: Walter-Herrmann, J., Büching, C. (Eds.), Fab Lab: of Machines, Makers and Inventors, Cultural and Media Studies. Transcript Verlag, Bielefeld, Germany, pp. 181–194.
Tuma, A., 1998. Configuration and coordination of virtual production networks. Int. J. Prod. Econ. 56-57, 641–648.
Vezzoli, C., Kohtala, C., Srinivasan, A., Diehl, J.C., Fusakul, S.M., Xin, L., Sateesh, D., 2014. Product-service System Design for Sustainability. Greenleaf Publishing, Sheffield, UK.
von der Gracht, H.A., Darkow, I.-L., 2010. Scenarios for the logistics services industry: a Delphi-based analysis for 2025. Int. J. Prod. Econ. 127, 46–59.
Webster, J., Watson, R.T., 2002. Analyzing the past to prepare for the future: writing a literature review. MIS Q. 26, xiii–xxiii.
Whittemore, R., Knafl, K., 2005. The integrative review: updated methodology. J. Adv. Nurs. 52, 546–553.
Wijekoon, K., Badurdeen, F., 2011. Modeling framework to evaluate sustainability performance of mass customized solutions. In: Chesbrough, H., Piller, F.T. (Eds.), Proceedings of the MCPC 2011 Conference. Presented at the 2011 World Conference on Mass Customization, Personalization, and Co-creation: Bridging Mass Customization & Open Innovation, San Francisco, CA.
Windt, K., 2014. Distributed Manufacturing. In: CIRP Encyclopedia of Production Engineering.
Xie, C., Bagozzi, R., Troye, S., 2008. Trying to prosume: toward a theory of consumers as co-creators of value. J. Acad. Mark. Sci. 36, 109–122.

Please cite this article in press as: Kohtala, C., Addressing sustainability in research on distributed production: an integrated literature review, Journal of Cleaner Production (2014), http://dx.doi.org/10.1016/j.jclepro.2014.09.039