Determining the Extent to Which Lean Principles are Integrated into Smart Manufacturing

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Abstract— This study explores to what extent the relinquishment and performance of smart manufacturing technologies builds on the relinquishment of lean principles. Primary explorative check data on the position of relinquishment of smart manufacturing technologies and lean principles and colorful functional performance issues were collected from a group of Dutch manufacturers and analyzed using Cluster Analysis, ANOVA, and Necessary Condition Analysis (NCA). The Cluster Analysis shows that while lean is additionally applied without smart(" lean-only " companies), smart technologies are substantially applied in confluence with lean(" lean and smart " companies), suggesting that the presence of lean principles is important for smart perpetration. A 3rd group of companies shows a low use of lean and smart ("non-adopters"). The NCAs further specify the extent of this necessity by showing that each one individual smart manufacturing technology used in our construct bear presence of lean principles, with MES systems having the strongest reliance. Performance wise, lean-only and lean and smart companies have similar superior performance compared to non-adopters when considering an aggregate functional performance measure using the confines of quality, delivery, inflexibility and price. When analyzed independently, the mixture position results remain true for quality and delivery performance. Still, for inflexibility, the prevalence of lean-only companies is more apparent, while for cost, lean and smart companies are superior. This shows that enforcing smart requires lean, but lean may serve counting on the specific performance objects strived for.

Index Terms—Industry 4.0, Lean principles, Necessary condition analysis, Operational performance, Smart manufacturing

I. INTRODUCTION

To remain competitive, companies are constantly searching for new generalities that can ameliorate the performance that's important in their assiduity. In recent decades, the operation of principles of lean thinking has steadily progressed and been extended to colorful assiduity and service sectors (Hines etal. 2004; Jasti and Kodali, 2014). This has been shown to appreciatively affect functional performance (e.g. Cua etal, 2001 Fullerton etal, 2014; Shah and Ward, 2003). presently, Assiduity4.0 technologies are fleetly changing product surroundings in numerous diligence(Kang etal., 2016; Porter and Heppelmann, 2015) and give farther openings to ameliorate functional performance(Brettel etal., 2014; Dalenogare etal., 2018; Szász etal., 2021).

The end of this study is to explore to what extent the relinquishment and performance of smart manufacturing technologies builds on the relinquishment of lean principles. To address this end, we specifically determine(1) the extent to which specific smart technologies bear the presence of lean principles, and (2) the detailed functional performance donation (quality, delivery, inflexibility and cost) of applying smart manufacturing technologies in combination with lean principles, compared to applying lean principles only.

Only many studies have reported on the necessity of lean for smart. By analyzing different clusters of companies grounded on different situations of lean and smart perpetration, some studies concluded that companies that extensively apply lean are more likely to borrow smart(Tortorella and Fettermann, 2018), thereby suggesting lean perpetration to be a easing condition for smart perpetration(Rossini etal., 2019). But it's yet unclear to what extent lean perpetration is needed to come smart, which justifies a more detailed analysis grounded on necessary conditions (Dul, 2016). A necessity relationship is relatively different from a interceding or a moderating one. However, it's part of the unproductive pathway between these two constructs, if a construct mediates the relationship between two other constructs. However, it can alter the direction or the strength of this relationship, if construct centrists the relationship between two other constructs. In discrepancy, a necessary condition indicates that in the absence of the condition, the outgrowth won't do, while the outgrowth isn't guaranteed if the condition is in place (Dul, 2016).

Studies reporting on the performance goods of the commerce between smart and lean are more multitudinous. Several recent studies have studied this grounded on empirical data (Buer etal. 2021; Kamble etal. 2020; Tortorella etal. 2019). The maturity of the studies report reciprocal performance goods of applying lean and smart (e.g. Buer etal. 2021; Chiarini and Kumar, 2021a; Dombrowski etal. 2017; Khanchanapong etal. 2014; Rossini etal. 2019; Tortorella and Fettermann, 2018). Other studies have further explored the type of commerce, which was shown to be a moderating effect of smart on the relation between lean and performance by several authors (Tortorella etal. 2018, 2019), while Kamble etal. (2020) set up an interceding effect of lean on the relation between smart and performance. Still, all these studies grounded their findings on added up performance measures. Thus, possible differences in goods between individual functional performance measures, similar as quality, delivery, inflexibility and cost, couldn't be observed.

II. LITERATURE REVIEW

Section2.1 provides background on the conception of smart manufacturing. Next, section2.2 reviews the recent literature that delved the relations between smart and lean and its impact on functional performance and shows the gaps in this literature that are addressed within this exploration.

2.1 Smart manufacturing

There's still relatively some nebulosity in the literature and in practice around the conception of Assiduity4.0 and its underpinning smart manufacturing technologies (Buer etal. 2018; Moeuf etal. 2018). The original vision of Assiduity4.0 formerly appeared in 1991. Weiser (1991) introduced the notion of ‘ubiquitous computing ’, where computers are integrated with each other and with the world, including product. More recent advances in ICT have now enabled integrated and cooperative manufacturing systems that combine the strengths of information, technology, and humans to be suitable to respond to changing circumstances in real time. This allows the physical world to get intermingled with the virtual world, performing in cyber-physical systems (Lee etal. 2015; Xu etal. 2018). These cyber-physical systems enable flexible and adaptive manufacturing processes by acquiring and recycling data, tone-controlling certain tasks, and interacting with humans via interfaces (Brettel etal. 2014).

To realize the vision of Assiduity4.0, numerous (new) specific Assiduity4.0 technologies are associated with it, similar as detectors, wireless communication, visual computing, independent robots, stoked reality, artificial intelligence, cumulative manufacturing, and more. This diversity of technologies doesn't contribute to the clarity of the conception. thus, several authors proposed ‘ crucial technologies ’(Alcácer and Cruz-Machado, 2019; Kang etal., 2016; Zhong etal., 2017) and/ or distributed technologies grounded on for case product lifecycle stages, operation areas(Frank etal., 2019), or functions within a data- driven para*digm(Klingenberg etal., 2021).*

Both Frank etal.(2019) and Klingenberg etal.(2021) distinguish between the more abecedarian enabling technologies or base technologies that induce, transmit, and store data and the more specific technologies or frontal- end technologies that apply this data in an artificial setting. Frank etal. (2019) described frontal- end technologies as defined subsets of technologies related to smart manufacturing, smart products, smart force chain, and smart working. Base technologies similar as the Internet of effects, pall services, big data, and analytics support the front- end technologies by furnishing connectivity and intelligence, which are characteristics that distinguish smart manufacturing from earlier manufacturing systems. Next to connectivity and intelligence, the literature mentions other smart manufacturing characteristics, similar as information translucency, decentralized opinions, and specialized backing(Hermann etal., 2016), and vertical, perpendicular, and end- to- end engineering integration (Brettel etal, 2014 & Wang etal , 2016).

These smart manufacturing characteristics enable companies to realize functional performance benefits (Brettel etal. 2014; Dalenogare etal. 2018; Szász etal. 2021). Within smart manufacturing systems, the connected product coffers(specialized and mortal) and their labors(i.e. products) induce data that can be participated with other coffers, converted into information, easily imaged, and used for intelligent decentralized mortal or independent decision making processes. Szász etal. (2021) empirically show that the perpetration of smart manufacturing technologies appreciatively impacts cost, quality, delivery and inflexibility.

2.2 Relation between smart and lean and its impact on functional performance

In recent times, further and further attention has been paid in the academic literature to the relationship between smart and lean. Buer etal.(2018) handed a first overview of this relationship through a methodical literature review of 21 papers within the also arising exploration area, which they structured by considering(1) how smart influences lean,(2) how lean influences smart,(3) the performance counteraccusations when integrating smart and lean, and(4) how environmental factors(e.g. repetitious versus on-repetitive terrain) affect an integration of smart and lean. Their review showed that utmost of the early literature studied the relation between smart and lean conceptually. Likewise, utmost studies took the point of view of how smart influences lean. Within this exploration sluice, smart technologies are shown to attack some of the failings of traditional lean systems and to support introductory lean styles and specific tools similar as just- by- time, Heijunka, Kanban, value sluice mapping, total productive conservation, single- nanosecond exchange of dies, visual operation, and poka- servitude(Mayr etal., 2018; Sanders etal., 2016; Wagner etal., 2017). More lately, Rosin etal.(2020) considered the impact of smart technologies on lean principles using a bibliographic exploration methodology and including the technologies ’ capability situations of monitoring, control, optimization, and autonomy as proposed by Porter and Heppelmann(2014). Using empirical data grounded on qualitative focus group sessions with assiduity experts, Cifone etal. (2021) linked underpinning mechanisms explaining how digital technologies can support lean practices.

Buer etal. (2018) showed that much lower attention had been paid to how lean can be used as a foundation for smart prosecutions. Still, it appears logical to first apply extra to streamline and simplify processes before automating the remaining value- adding exertion (Bortolotti and Romano, 2012). In light of our disquisition end to explore the extent to which lean performance is demanded to come smart, the distinction between how smart influences lean, or how lean influences smart, is not applicable. In both cases, smart may bear presence of lean principles.

Several recent studies have empirically vindicated the early results reported in Buer etal. (2018) concerning the complementary performance goods of combining lean and smart (Bueretal. 2021; Chiarini and Kumar, 2021a; Rossinietal. 2019; Tortorella and Fettermann, 2018; Yilmazetal. 2022). This implies that extra should not be substituted by smart, since there is fresh value in the combination. Whereas Chiarini and Kumar (2021a) used qualitative interview and observation data and Yilmaz etal. (2022) analyzed case studies linked from the literature to show how the integration of smart and lean can give performance benefits, the other studies mentioned used a check approach to determine the complementary performance goods. While these check- predicated studies all incorporated a set of individual functional performance measures (e.g. productivity, delivery service position, force position, quality, strictness, etc.), these were added up into a single functional performance construct that was subsequently used in the analyses. As a result, no findings were reported on the complementarily of smart and lean at the individual performance position.

Other recent studies have shown moderating goods of administering smart on the relation between lean and performance. Tortorella etal. (2018) concentrated on the external process factors of lean, relating to the supplier and customer, within the Brazilian sedulity. They specifically set up a moderating effect for customer- related lean practices. In addition, Tortorella etal. (2019) concentrated on three internally related lean practice packets of Shah and Ward (2007) within the Brazilian sedulity and they included four contingency factors. Their findings show that technologies related to products or services positively moderate the effect of flux practices on functional performance. Both studies analyzed performance impacts using a single added up performance construct.

Numerous studies relating smart and lean looked at performance patterns and the necessity of lean for smart. Yilmaz etal. (2022) reviewed 42 case studies mentioned in the literature to explore the profitable, social, and environmental benefits, walls, and success factors of integrated smart and lean prosecutions. They showed that lean principles were applied before smart in 50 of the cases, there was a simultaneous operation in 40 of the cases and smart was applied first in only 10 of the cases. Tortorella and Fettermann (2018) used cluster analyses to distinguish groups of companies differing in two situations (low & high) of lean performance position, smart performance position, and performance improvement over the last 3 times. One of their findings was that high smart performance was rarely set up in low lean performance settings. Also Rossini etal. (2019) set up in a similar study setup with European manufacturers, that the handover of smart was significantly linked to lean performance, while lean performance was independent from smart performance. While they stated that advanced lean performance ‘appears as a necessary condition’ for smart performance, they did not assay the conditions using necessity sense, nor did they consider this for specific smart technologies.

III. EXPERIMENT AND RESULT

This section describes and motivates all main way performed in the research. However, the results are integrated with (or reported incontinently after) the description of a step, If applicable.

3. 1.Questionnaire development and measures

To answer our exploration question, primary data was collected through check exploration. To insure the validity of the questionnaire, the scales were tested in two ways. We first asked ten experts in the field of lean and smart technologies to assess the check questions. Grounded on their feedback, small variations have been made, substantially in relation with the questions on smart technologies (wording and fresh exemplifications). Secondly, we conducted an airman check by reaching 24 manufacturing companies. The end of the airman check was to insure that the questions were meaningful in a variety of different diligence. After filling the questionnaire, we canvassed the repliers and all agreed that the check captured their understanding of both lean principles and smart assiduity technologies. Descriptive statistics of the data gathered during the airman check don't differ significantly from the final dataset. The small chance of missing values in the final dataset provides farther substantiation of the clarity of the check questions. The final check questions used to collect data are handed in the excursus.

The use of private and tone- reporting measures raises enterprises about implicit common system bias. Podsakoff etal. (2003) proposed a set of ways for controlling and reducing similar implicit negative goods. In terms of the study design, to avoid undesirable art factual covariance between different variables, questions were separated from each other in the questionnaire. To further reduce the liability of system bias in the study design, the exploration design was presented to implicit repliers as a study aiming at understanding the position of perpetration of smart technologies and lean principles. The end of assessing to what extent smart manufacturing builds on lean principles and their goods on functional performance wasn't mentioned, so that repliers' attention wasn't drawn to the main objects of this study. In terms of repliers, we targeted the potentially most knowledgeable repliers grounded on the directorial position (e.g., CEO, product director, design director) and asked them to answer questions as actually as possible, and allowed them obscurity. In this way, we aimed to minimize implicit impulses related to strange terms and at the same time reduce any apprehension that the repliers might have that could lead to them furnishing socially desirable answers. Eventually, we employed different scale anchors and formats to measure practices’ relinquishment and performance.

3.2. Measures

Our smart manufacturing technologies construct is operationalized as a first- bid 5- sub item reflective variable. The five particulars are ‘Work- on- screen results’, ‘Product shadowing’, ‘Information systems’, ‘ MES systems’, and ‘Flexible robotization’, which can be related to the factors of a smart plant's reference armature, as developed by Yoon etal.(2012). They linked the following ubiquitous factors of au-Factory(smart plant)u-Human-Resource,u-Product,u-MES(manufacturing prosecution system), data accession and transmission on the shop bottom as device to the ubiquitous system(D2U), and an information exchange structure(UPLI ubiquitous product lifecycle information trace) where information is transmitted, changed, and recaptured by colorful stakeholders in colorful stages of the product lifecycle. Table 1 provides an overview of the factors included in our smart manufacturing technologies construct, with a description and exemplifications.

Table 1. Smart manufacturing technologies.

Component	Description	Examples
Work-on-screen solutions [u-Human]	'Interface devices to provide Operators with information anywhere, anytime for comfortable and safe working environment' (Yoon et al., 2012, p. 2180).	Use of digital assistance systems to present information(e.g. digital work instructions, drawings, part lists, real-time status information, etc.), on desktop computers, laptop, tablets, smart glasses and/or Smart phones.
Product tracking [u-Product]	Products can be identified and are accessible to manage information on status or location in real time (Yoon et al., 2012).	Digital tracking of location or status of products through technologies such as RFID, Bluetooth Low Energy or Ultra-Wideband beacon technology Or barcodes.
Information systems [UPLI]	Existing information system, such as enterprise source development and customer correlation management, are essential to ensuring horizontal and vertical assimilation (Wang et al., 2016).	Transaction processing systems that support business processes, such as CRM (supporting required actions towards the customer) and ERP (supporting \e.g. order fulfillment and Inventory control).
MES systems [u-MES]	'Application systems to manage and Control the whole shop floor' (Yoon et al., 2012, p. 2180).	Digital initiation of actions using real-time data from shop floor processes and underlying operations to support, control, and integrate shop floor Processes.
Flexible automation [u-Resource]	Digitized and interrelated material resources (Lee et al., 2015).	Interconnected machining centers, robots, automatic guided vehicles, etc.

The lean principles construct is operationalized as a first- order 4- item reflective variable. The four particulars related to the four rules deduced from the Toyota Production System by Spear and Bowen(1999)(1) a direct client- supplier connection,(2) standardization of products and processes,(3) inflow product and reduced outturn times, and(4) nonstop enhancement. Compared to the five principles developed by Womack and Jones (1996) and the 14 principles developed by Liker (2004), the four rules by Spear and Bowen concentrate more on the factual geste as it's manifested by workers on the shop bottom. Compared to more expansive instruments on lean practices (e.g. Shah and Ward, 2007, 2003), these principles represent a further abstract view on the extent that lean is present in an association. Given the different set of associations in our sample, this representation is considered more suitable.

Functional performance is operational zed as a 4- item constructive variable. A constructive measure of functional performance is harmonious with the previous literature (e.g. Bozarth etal., 2009). The four particulars are quality, delivery, inflexibility and cost (Slack etal. 2010). The present study focuses on functional performance as an aggregate measure, but also on the single confines independently.

All questions (except for the generics) were scored on a 9- point Likert scale to collect interval data (Karlsson, 2009) and, given the single questions per conception, to overcome dimension error (Finstad, 2010). Questions related to orders 2 and 3 were ranked on a scale anchored at 'not' (1), 'kindly

' (5) And 'vastly' (9). An illustration is "To what level do you use the lean principle 'nonstop enhancement' in your company?" " Questions related to order 4 were ranked on a scale anchored at ' worse '(1), ' average '(5) and ' better '(9). An illustration is "How does your company score on firmness compared to your assiduity peers?" All check questions were restated into Dutch to insure that all actors could understand the generalities surveyed.

3.3. Sample and data collection

The check was distributed to a stratified arbitrary sample of small, medium, and large Dutch manufacturing companies via the online check tool Qualtrics. Manufacturing was defined using the bracket of profitable conditioning in the European Community (generally appertained to as NACE) as 'Level 1, Group C Manufacturers' (European Commission, 2010). 120 repliers filled in the questionnaire, this is considered sufficient for our Conformational factor analysis(CFA)(Fornell and Larcker, 1981), Cluster Analysis and ANOVA(Hair etal., 2014), and NCA(Dul, 2016), and above other tentative papers on either smart technology(e.g. Reyes etal., 2012), lean operation(e.g. Phan etal., 2011) or functional performance(e.g. Merschmann and Thonemann, 2011). Primary tests on our dataset have been carried out to give substantiation on the validity of the questionnaire and the sample. The check was administered to directors and directors of 1000 companies, indicating a 12 response rate that can be considered respectable (Dillman, 2011). To rule out anon-response bias, we compared the responses of the first 50 per cent of repliers against the last 50 per cent. All the t- tests were non-significant, thus we concluded that on-response bias isn't an issue. We checked the qualification of the repliers to insure that their directorial positions were acceptable to guarantee a certain position of knowledge regarding functional practices perpetration and factory performance compared to challengers. Repliers were most constantly possessors CEOs or product directors. In the sample, 36 of the 120 companies were large (≥ 250 workers), 57 were medium- sized (50 – 250 workers) and 27 were small (< 50 workers), while two repliers didn't mention their company size. The average founding time was 1954, with large companies on normal being kindly aged than small companies. Companies came from process and separate diligence (e.g. chemicals, plastics & rubber, food, tobacco, automotive, consumer & ménage products, essence workshop, artificial & structure material, high- tech, and ministry) for business- to- business and business- to- consumer requests. We compared our number of cases per assiduity with the sectoral analysis of manufacturing (Eurostat, 2018) and set up it to be representative. The characteristics of the companies and repliers in our sample are epitomized in Table 2.

Table 2 Overview of generics: founding year, size in FTE, company industry, and respondent function.

Empty Cell	**in.**	**Avg.**	**Max.**
Founding year	*1812*	*1954*	*2016*
Large companies (30%)	1819	1928	2016
Medium-sized companies (47.5%)	1812	1955	2013
Small companies (22.5%)	1946	1988	2015
Size in FTE	*10*	*2.063*	*112.000*
Large companies (30%)	250	6.118	112.000
Medium-sized companies (47.5%)	50	123	224
Small companies (22.5%)	10	26	45
	Percent		**Percent**
Company industry (Eurostat)		*Respondent function*	
Machinery and equipment	12.39	Owner/CEO	17.8
Fabricated metal products	11.5	Production Manager	16.95
Empty Cell	**in.**	**Avg.**	**Max.**
Food products	9.73	Project Manager	11.86
Electrical equipment	9.73	Consultant	6.78
Motor vehicles, trailers and semi- trailers	7.08	Production Engineer	5.08
Basic metals	6.19	Lean/Six Sigma Manager	5.08
Repair and installation of machinery and equipment	6.19	R&D Manager	4.24
Rubber and plastic products	5.31	Other	4.24
Other manufacturing	5.31	Plant Manager	3.39
Basic pharmaceutical products	3.54	Quality Manager	3.39
Other transport equipment	3.54	Process Engineer	3.39
Furniture	3.54	Sales Engineer	2.54
Other non-metallic mineral products	2.65	Accountant/Controller	2.54
Beverages	2.65	Team Leader	2.54
Printing and reproduction of recorded media	2.65	Account Manager	1.69
Coke and refined petroleum products	1.77	Service Manager	1.69
Tobacco products	1.77	Supply Chain Manager	1.69
Paper and paper products	0.88	Mechanical Engineer	1.69
Wood and products of wood and cork	0.88	Product Manager	0.85
Textiles	0.88	Manager Engineering	0.85
Wearing apparel	0.88	R&D Engineer	0.85
Leather and related products	0.88	Lean/Six Sigma Engineer	0.85

3.4. Dimension model validity and trust ability

Before testing the dimension model validity, we screened our data and vindicated the normalcy supposition. Descriptive statistics reported in the excursus give substantiation of normalcy of our data. Specifically, all skewness and kurtosis absolute values were below0.99 and1.31, independently, values well below the generally accepted thresholds (Muthen and Kaplan, 1985). To test the validity and trust ability of the construct measuring smart manufacturing technology and lean principles (the dimension model), a CFA was performed using STATA16.1 (Jöreskog, 1969). Although the results of the CFA indicated that the complete set of particulars was respectable to measure our constructs(χ^2 = 54.76; df = 27; χ^2/ df =

2.03; CFI = 0.941; SRMR = 0.110; RMSEA = 0.092), the analysis of the revision indicators revealed that one item measuring smart manufacturing technology(Information systems) was problematic in terms of cross-loading. A possible explanation of the cross-loading is that Information systems, defined as digital suggestion of needed conduct towards the client (CRM) and towards copping and product processes(ERP, shop bottom control), are generally used in numerous manufacturing companies, not only in companies espousing smart technology, and thus it's a common technology for lean companies too, singly on their position of smart technology relinquishment. Following judgmental criteria (Wieland etal., 2017) and considering the content of the remaining particulars (content validity) (Hair etal., 2014), it was decided to cancel this item as the content validity wasn't compromised, while all the fit indicators of the CFA bettered significantly, showing strong validity of the measures ($\chi 2$ = 34.03; df = 20; $\chi 2$/ df = 1.70; CFI = 0.967; SRMR = 0.073; RMSEA = 0.076). Coincident validity is guaranteed by having all factor ladings and average friction uprooted (Adieu) advanced than0.50 (Fornell and Larcker, 1981). Discriminate validity is verified since both Adieu values are above the participated friction of the two constructs (Fornell and Larcker, 1981). Eventually, compound trust ability measures guarantee internal trust ability as both are above the0.70 cut- off (Hair etal. 2014). These measures are given in Table 3.

Table 3. Data quality measures.

Construct	Factor loading	Average variance extracted	Composite reliability
Smart manufacturing technologies		*0.53*	*0.82*
Flexible automation	0.69		
MES	0.85		
Product tracking	0.70		
Information systems	–		
Work-on-screen	0.66		
Lean principles		*0.70*	*0.90*
Supplier and customer link	0.57		
Standardization	0.87		
Flow	0.91		
Continuous improvement	0.85		

3.5. Using a one-way ANOVA and cluster analysis

In order to (1) determine the types of lean manufacturing principles and smart manufacturing technologies implementation patterns that can be found in our sample and (2) determine whether different implementation patterns result in differences in operational performance outcomes, a two-step cluster analysis and a series of one-way ANOVA tests were used. A two-step cluster analysis was used to find several groups. By calculating the percentage change in the agglomeration coefficient when the number of clusters is decreased, the first stage (hierarchical clustering) determines the number of clusters in the data. Non-hierarchical clustering, the second phase, produces the clusters themselves (Hair et al., 2014). This cluster analysis technique is similar to those used by Flynn et al. and other cluster analysis instances (2010). Up until it dramatically increased from a three- to a two-cluster solution, the agglomeration coefficient of the hierarchical clustering was stable or declining (31 per cent). This result indicated that our sample contained three clusters. Three clusters, as determined by a random sample of dendrograms, were the ideal option. Companies were divided into three categories in the subsequent phase (k-means). Then, we used a series of one-way ANOVA to distinguish between the three clusters based on differences in the degrees to which smart manufacturing technologies and lean principles were applied, as well as in terms of operational performance outcomes (measured as both an aggregate dimension and as individual performance dimensions of Quality (Q), Delivery (D), Flexibility (F), and Cost (C).

3.5.1. Implementation patterns that follow and operational performance results

The outcomes of the two-step cluster analysis and several one-way ANOVA tests are presented in Table 4.

Table 4. Comparing the three categories that the cluster analysis produced.

Empty Cell	N	Lean	Smart	Size	PERF	Q	D	F	C
Group 1 Non-adopters	37	$4.58^{a,b}$	3.28^{a}	4.47^{a}	$5.67^{a,b}$	$6.36^{a,b}$	$5.03^{a,b}$	6.64^{c}	4.69^{c}

Empty Cell	N	Lean	Smart	Size	PERF	Q	D	F	C
Group 2 Lean-only	34	7.25^{a}	3.64^{b}	4.66^{c}	6.75^{a}	7.38^{a}	7.03^{a}	7.62^{c}	4.94^{d}
Group 3 Lean and smart	49	7.27^{b}	$6.38^{a,b}$	$5.72^{a,c}$	6.82^{b}	7.25^{b}	7.06^{b}	7.04	$5.72^{c,d}$

Mean difference testing using pair wise comparisons by Sheffe.

a,b: p-value < 0.01; c: p-value < 0.05; d: p-value < 0.10.

The results of the cluster analysis show that there's a group of companies that don't borrow lean and smart(group 1 named “non-adopters ” characterized by companies with a low use of lean and smart technology). likewise, we set up that lean principles are frequently applied alone(group 2 named “ lean-only ” characterized by companies with a high use of lean and a low use of smart technology), this isn't the case for the use of smart technologies as they're seen in confluence with lean(group 3 named “ lean and smart ” characterized by companies with a high use of both lean and smart technology). likewise, a group of smart-only companies isn't apparent.

In terms of functional performance, when considering the confines of quality, delivery, inflexibility and cost as a total and constructive construct, the results show that lean-only and lean and smart companies have similar superior performance compared to the non-adopters. still, when analyzing performance confines independently, the superior and similar results set up at the aggregate position remain true only for quality and delivery performance. Regarding inflexibility, lean-only companies are superior to the non-adopters, while lean and smart companies don't separate mainly from the non-adopters although not performing significantly worse than lean-only companies. Regarding cost rather, lean and smart companies are superior to the non-adopters, while lean-only companies don't separate mainly from the non-adopters and perform worse than lean and smart companies at a 90 confidence position.

When considering the size of the companies within the clusters, results show that there's a significant difference in the size of the companies, reckoned in the logarithm of FTE. In fact, smart and lean companies are significantly larger than the other groups, while lean-only and non-adopters don't significantly differ. Fig. 1 provides a visual overview showing that the largest companies are generally set up in the smart and lean group. With SMEs(FTE< 250), the variation in use of lean and smart is advanced. Fig. 1 also shows that, for all company sizes, the position of exertion in the field of smart manufacturing is generally lower than that for lean the round blotches are generally lower than the affiliated triangles. Interestingly, a qualitative check of the assiduity representation in the three groups doesn't show any apparent difference as companies operating within the same or analogous assiduity are distributed across the three groups, and within the same group companies operate in a variety of different diligence.

3.6. Necessary Condition Analysis

To consolidate the results from the cluster and ANOVA analyses and specify the extent to which smart requires lean, we ran a Necessary Condition Analysis(NCA)(Dul, 2016) for each individual item within our construct of smart manufacturing technology. A necessary condition(then use of lean principles) enables the outgrowth(then use of smart technology) when present and constrains the outgrowth when absent(Dul etal., 2020). In discrepancy to regular retrogression analyses that study variables in a probabilistic relationship to each other, an NCA allows the study of variables that are necessary but no guarantee for a certain outgrowth to do. The NCAs in this study therefore linked the extent to which using lean principles is necessary for using each of the smart manufacturing technologies included in our construct.

An NCA starts with drawing a ceiling line through the upper- left compliances of an x-y plot. As the data are nonstop, a ceiling retrogression line(CR- line) is used(Dul, 2016). This line separates the ‘ empty space ’ and the ‘ full space ’ of the dataset(Goertz etal., 2013) indicating the degree to which a smart manufacturing technology(y- axis) could be enforced without the presence of lean principles(x-axis).Fig. 2 shows the x-y plots for the use of lean principles and smart manufacturing technologies. The solid orange lines represent CR- lines, which define the empty space. The larger the empty space(relative to the total space with compliances), the further X(then use of lean principles) constraints Y(then smart manufacturing technology).

2. NCA plots of lean principles for different Smart Manufacturing Technologies.

To determine the validity and significance of the ceiling lines, the rigor, effect sizes and p- values were calculated. These measures are given in Table 5. The rigor(> 95) were set up sufficient to use the CR lines in the NCA(Dul, 2016). The effect sizes exceeded the threshold of0.1 and were set up to be moderate(0.1 – 0.3) to large(>0.3), indicating an enabling effect of the conditions on the outgrowth. After running the approximate permutation test with10.000 re samples, the p- values(Dul etal., 2020) were set up to be significant(<0.050).

Table 5. NCA validity and significance measures.

Construct	Accuracy (%)	Effect size	p-value
Lean principles – Work-on-screen	99.2	0.146	0.045
Lean principles - Product tracking	96.9	0.242	0.011
Lean principles - MES systems	95.3	0.375	<0.001
Lean principles - Flexible automation	97.6	0.254	0.003

NCA's tailback table is used to efficiently represent all ceiling lines of the different smart technologies numerically(see Table 6 in Section3.6.1). The first column represents the outgrowth position Y(presence of smart technology) and the coming columns represent the threshold position of condition X(presence of lean principles) for each of the smart manufacturing technologies. The first row represents the smallest position of Y in the range of compliances, the last row the loftiest position. Per row(particular position of Y), the threshold situations of condition X can be read for each smart manufacturing technology. We give the situations of X and Y both as percentiles and as probabilities, since percentiles say further about the population of companies whereas probabilities might be more intriguing for individual companies.

When applying percentiles, the situations of Y in the first column are expressed as percentiles, ranging from 0 to 100. Next, for each percentile position of Y, the percentile position of X is handed. This represents the chance of companies that weren't suitable to achieve the necessary position of condition X for the given position of Y(with the factual number of companies handed between classes). thus, the percentile for X is an index of the significance of the necessary condition. A0.0(0) indicates that all companies were suitable to reach the required position of X for the corresponding position of Y.

When applying probabilities, the X and Y values of each of the ceiling lines are restated into probabilities of the range of compliances. The first column also shows a 0 – 100 range of the observed maximum use of the smart technology and the coming columns show which chance of the observed maximum use of lean principles is needed to reach the asked position of the particular smart technology. NN denotes that lean principles aren't needed(Not Necessary) for the asked position.

This system of analysis slightly deviates from other exemplifications of NCA operation. Knol, Slomp etal.(2019b) linked the relative significance of enhancement routines for developing lean practices, Sousa and da Silveira(2017) set up necessary degrees of services in the process of servitisation, and Van der Valk etal.(2016) determined the criticality of contracts and trusts for supplier relations. similar studies consider several conditions as necessary for one outgrowth. In discrepancy, this study considers one condition(presence of lean principles) for several issues(presence of different smart manufacturing technologies).

3.6.1. Performing dependences of smart on lean

Table 6 shows the results of the NCA analyses for each individual item within our construct of smart manufacturing technology in a tailback table. The first column shows the outgrowth position Y, indicating the position of presence of the smart manufacturing technology. The remaining columns show the percentiles and probabilities of the situations related to the presence of lean principles for each of the specific smart manufacturing technologies.

Table 6 tail back table with situations of presence of Smart manufacturing technology and situations of presence of lean principles as percentiles and probabilities for different Smart manufacturing technologies.

Smart manufacturing technology [y]	Lean principles [Work-on-screen]		Lean principles [Product tracking]		Lean principles [MES systems]		Lean principles [Flexible automation]	
	Percentile	%	Percentile	%	Percentile	%	Percentile	%
0	0.0 (0)	NN	0.0 (0)	NN	0.0 (0)	NN	0.0 (0)	NN
10	0.0 (0)	NN	0.0 (0)	NN	0.0 (0)	4.6	0.0 (0)	NN
20	0.8 (1)	NN	0.0 (0)	NN	0.0 (0)	12.8	0.0 (0)	NN
30	1.6 (2)	0.4	0.0 (0)	NN	0.0 (0)	21	0.0 (0)	NN
40	1.6 (2)	6.2	1.6 (2)	2.3	0.0 (0)	29.2	0.0 (0)	9.1
50	1.6 (2)	12.1	2.4 (3)	14.9	1.6 (2)	37.4	1.6 (2)	20
60	3.9 (5)	17.9	8.7 (11)	27.6	2.4 (3)	45.6	2.4 (3)	30.9
70	3.9 (5)	23.7	19.7 (25)	40.3	8.7 (11)	53.8	9.5 (12)	41.7
80	8.6 (11)	29.6	19.7 (25)	53	14.2 (18)	62	23.8 (31)	52.6
90	8.6 (11)	35.4	38.6 (50)	65.7	26.8 (35)	70.2	23.8 (31)	63.5
100	12.5 (16)	41.2	52.8 (68)	78.3	66.1 (85)	78.4	61.9 (80)	74.3

The tailback table easily shows three effects. First, when fastening on the loftiest position of presence of the smart manufacturing technologies in the range of compliances(100th percentile), numerous companies didn't have the needed situations of lean to achieve this position for product shadowing, MES, and flexible robotization(68, 85 and 80 companies, independently). Looking at the probabilities, full presence(100) of perpetration of smart manufacturing technologies was accompanied by a high(≥74.3) degree of operation of lean principles for these three smart manufacturing technologies. Only for work- on-screen, all but 16 companies in our dataset had sufficient situations of lean to be suitable to achieve the loftiest position(100th percentile) of this smart technology. For work- on- screen a kindly lower degree of operation of lean principles(≥41.2) was needed to achieve the loftiest position(100). This indicates that for product shadowing, MES and flexible robotization, presence of lean principles is necessary and veritably important for companies. No companies used product shadowing, MES, or flexible robotization ‘ vastly ’(≥ 90) without also using lean principles ‘ vastly ’(≥63.5).

Alternate, when fastening on the lower situations of presence of the smart manufacturing technologies in the range of compliances, the companies(all but two or three) in our dataset had the needed situations of lean to at least incompletely(up to 50th percentile) apply the smart technology. still, indeed low situations of MES(≥ 10) were only achieved with at least some presence(≥4.6) of lean principles. For work- on-screen, product shadowing and flexible robotization, low situations(< 30) of use could be achieved without presence(NN) of lean principles. This means that formerly for low situations of MES, presence of lean principles is necessary. For low situations of the other smart technologies, presence of lean principles is less important and needed situations are achieved formerly.

Third, when fastening on the presence of the smart manufacturing technologies between the 40th and 70th percentile(mid-range), it can be observed that companies didn't always meet the needed situations of lean principles. For a asked position of 40 or further, all smart technologies needed at least some presence(2.3 –29.2) of lean principles, indicating that decreasingly, perpetration of these technologies needed presence of lean principles. The presence of lean principles in this mid-range seems most important for product shadowing, indicated by the loftiest percentile situations of lean principles(representing the chance of companies that weren't suitable to achieve the necessary position of presence of lean principles for the given perpetration position of the smart manufacturing technology).

4. DISCUSSION AND CONCLUSIONS

The end of this paper was to explore to what extent the relinquishment and performance of smart manufacturing technologies builds on the relinquishment of lean principles. thus we considered the extent to which specific smart technologies bear the presence of lean principles and the performance donation of smart in terms of the performance confines of quality, delivery, inflexibility and cost.

4.1. The extent that lean is necessary for smart

While some earlier studies have shown that the relinquishment of smart was linked to lean perpetration(Rossini etal., 2019; Tortorella and Fettermann, 2018), our findings give a more elaborate view on the extent of this reliance for different types of smart manufacturing technologies. The Necessary Condition Analysis(NCA) for each individual item of smart manufacturing technology included in our construct(work- on- screen, product shadowing, MES systems, and flexible robotization) showed that they all bear lean principles to realize high perpetration situations, with the strongest goods for product shadowing, MES systems, and flexible robotization. lean principles are therefore set up necessary for the operation of smart technologies. Only low situations of smart technology perpetration were achieved without lean perpetration(with the smallest position for MES), indicating that the operation of lean is a necessary condition to apply smart.

Although our study didn't give any qualitative data to explain the underpinning mechanisms that lead to the reliance of smart on lean, other recent literature has handed some possible explanations. From 21 pollsters and 216 repliers, Chiarini and Kumar(2021b) explain that the maturity agreed that, for illustration, smart detectors and RFID technologies were helpful to ameliorate processes. One of their exemplifications shows that similar technologies allowed them to identify and trace products and packaging, and indeed tools and people. This latterly helped the company to impeccably trace who made which product, with which tools, to reduce crimes and blights and ameliorate their processes. Also, Chiarini and Kumar(2021b) set up that MES systems helped to halt machines in case of nonconformities, precluding farther blights and allowing for root cause problem working. From ten interviews and an in- depth case study, Chiarini and Kumar(2021a) set up that it's important to first reevaluate the product layout and reduce waste, and also automate this process with robots, automated vehicles, and similar. In general, they set up that there was a common understanding that smart technologies can only be enforced after streamlining and creating inflow in processes, thereby also attesting the finding of Bortolotti and Romano(2012) that processes should be streamlined with lean before pursuing robotization.

4.2. The specific performance donation of smart compared to lean

The findings of our study show that when functional performance is considered as a total and constructive construct of the confines of quality, delivery, inflexibility and cost, enterprises that apply lean-only or lean and smart realize similar and superior performance compared to enterprises that don't borrow lean and smart. These findings are in line with earlier literature showing performance advancements when enforcing lean(e.g. Cua etal., 2001 Fullerton etal., 2014; Shah and Ward, 2003), but discrepancy with literature stating that enforcing lean and smart results in superior performance compared to enforcing lean-only(Buer etal., 2021; Tortorella etal., 2019, 2021a). Only when looking more specifically at the individual confines of performance, we set up superior cost performance of enforcing lean and smart compared to only enforcing lean.

Our findings show that smart-only executions generally don't do in practice, while lean-only could be just as good an approach as lean and smart when the end is to ameliorate the lower performance situations of quality and delivery in the beach cone of accretive performance or indeed the inflexibility position. Only to achieve cost isolation smart technologies need to be added. This means that lean and smart(lean robotization) may not always be the applicable path for the future, supposedly there are also circumstances where it's sufficient to apply lean and where smart technologies are thus not rigorously necessary.

Fresh findings related to company size as a contextual factor corroborate with earlier exploration findings. On average, large companies use smart manufacturing technologies and lean principles more considerably than lower companies. Supposedly, conditions similar as the presence of sufficient knowledge, time, and plutocrat are more favorable at larger companies. For smart technologies, this observation aligns with the finding of Szász etal.(2021) that larger companies invest further in enforcing Assiduity4.0 technologies than lower bones

And with the statement of Rüttimann and Stöckli(2016), who claimed that SMEs won't fluently profit from Assiduity4.0 due to the large investments needed. Likewise, Rüttimann and Stöckli(2016) stated that Assiduity4.0 enables large companies to fulfill lower customized demands, which were preliminarily generally fulfilled by SMEs.

4.3. Theoretical benefactions and practical counteraccusations

With respects to proposition, our exploration showed the extent to which smart manufacturing technologies bear presence of lean principles a high use of smart manufacturing technologies requires a high use of lean principles and indeed for low situations of smart perpetration some lean perpetration is needed. Smart-only executions were generally absent. These findings add to the extant literature that describes the interceding and moderating relations between lean, smart, and performance. In this regard, this study adds further nuance to the relation between lean and smart and the significance of the presence of lean when aiming to apply smart manufacturing technologies.

In practical terms, this exploration has counteraccusations for directors, preceptors, and policymakers. For directors, the dependences between these generalities can help to decide in what to invest, and in which sequence. To a certain extent, this depends on their points; if they aim for performance isolation in the lower layers of the beach cone model of accretive performance(e.g. quality and delivery), the presence of lean principles seems sufficient. If they aim for performance isolation in the advanced layers of the beach cone model of accretive performance(e.g. inflexibility and cost) and specifically aim to realize low costs, combining lean principles with smart manufacturing technologies is recommended.

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