On the versatility of Little's Law in operations management: a review and classification using vignettes

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Abstract

Despite Little's Law being considered as one of the 'laws' of operations management, evidence of its application in an empirical context is diverse and diffuse. Hence, this paper aims to identify, classify and consolidate published empirical applications of Little's Law in a systematic manner to better understand its versatility. This paper undertakes a systematic literature review of the databases of the five main publishers of operations management journals, plus snowball sampling for additional papers. A final sample of 128 empirical journal articles is identified and categorized. Tactical, medium-term decisions relating to capacity dynamics and operations re-engineering are the most popular categories. To give further insights into versatility, vignettes for each category are developed. The review and vignettes confirm Little's Law as a highly relevant paradigm to operations management decisions due to its empirical versatility across levels, sectors and time domains. The paper suggests four factors to underline the empirical versatility of Little's Law in operations management: applicability, utility, simplicity and visibility.

Keywords: Systematic review; law of manufacturing; Factory Physics; Production systems; WIP.

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This was Professor Denis Towill's (1933 – 2015) final paper. He initiated our work related to Little's Law and made substantial contributions to the first draft of this paper before he passed away. On behalf of those working in the Logistics Systems Dynamics Group at Cardiff, we would like to acknowledge his contribution to our lives and careers.

1. Introduction

The application of operations research (OR) techniques into production systems is considered to have become more widespread with the advent of the Second World War and continues to be applicable today. One such tautology that has transferred is Little's Law (Little 1961), which states $L = \lambda W$, where L = number of items in the queueing system, λ = average arrival rate and W = average time spent in the system. This relationship holds regardless of (Kanet 2004; Sztrik 2010; Little 2011):

- arrival and service time distributions;
- number of servers and queueing disciplines;
- infinite and finite time periods, although the number of items in the system and their average age needs to remain constant;
- whether the focus is on the system as a whole, sub-systems and/or specific classes of customer.

While much of the work on Little's Law has focused on stationary values, there has also been research into its distributional form, examining whether the distributions of L and W are related. Notable work in this area includes Haji and Newell (1971) and Bertsimas and Nakazato (1995) although, as Little (2011) notes, the conditions for the distributional form of Little's Law to apply are quite restrictive.

The transfer of the tautology to the OM community can be attributed to Hopp and Spearman's *Factory Physics* (Little and Graves 2008). Hopp and Spearman (2008) express Little's Law in terms of work-in-progress (L), throughput (λ) and cycle time (W). This attributing to *Factory Physics* is not to overlook earlier examples where this same relationship is expressed (for example, Hall 1983; Wacker 1987), but these sources do not explicitly mention Little. Hopp and Spearman (2008) provide a number of suggested uses, including calculating queue lengths, measuring and reducing cycle time, managing inventory levels and evaluating backlogs.

The relationships explained by Little's Law provide an underpinning to approaches used in the pursuit of effective process flows by firms (Afy-Shararah and Rich 2018) and concepts such as Lean Thinking (Womack and Jones 1996) and swift and even flow (Schmenner and Swink 1998) continue to be deployed some 20 years after their popularisation. Hence, Little's Law remains

relevant to OM practitioners and scholars today, with examples of this in journal papers (Lödding and Piontek 2018), academic books (Holweg et al. 2018), practitioner books (Modig and Åhlström 2012; Pound, Bell and Spearman 2014), blogs (Mulholland, 2017), and university teaching (Dobson and Shumsky 2006; Lapré 2010).

Given the breadth of awareness, this paper aims to *identify, classify and consolidate published empirical applications of Little's Law in a systematic manner to better understand its versatility*. We establish two research questions to be addressed in the paper:

1. Do the applications of Little's Law demonstrate empirical transferability to enable it to represent a 'law' of OM?
2. What factors contribute to the versatility of Little's Law in operations management?

The first question considers empirical transferability, which can be defined as the ability to be applied in a range of different empirical settings and reflects the sentiment of Micklethwait and Wooldridge (1996) when considering good management theory. The question is addressed through a systematic literature review, giving a structure by which versatility between different research studies can be examined. Question two draws on a qualitative analysis derived from vignettes of relevant research papers. Versatility relates to the ability to be adapted to different situations, and therefore having this attribute enables Little's Law to successfully transfer between empirical settings.

An initial motivation for this study came from Little himself who observed that 'there is no ready source of written material of this sort [giving evidence of practice] for a specialized topic like Little's Law' (Little 2011, p536) and more recently 'Little's Law has many applications, mostly unreported' (Little 2013). However, there are a broader range of gaps that this paper seeks to address, and these are summarised in Table 1.

Area	Relevance of Little's Law	Example References	Identified gaps this paper addresses
Operations Research Theory	• Proven principle connecting three key variables in queuing theory	Whitt (1991); Wolff (2011)	Reviews only focus on the theoretical applications of Little's Law
Operations Management Theory	• Informs knowledge about fundamental behaviour of processes • Tentatively considered as a law	Klassen and Menor (2007); Schmenner and Swink (1998)	Lack of synthesis of empirical work to evidence good management theory
Operations Management Text Books	• Incorporated into lean principles • Incorporated into Factory Physics • Incorporated into process management text books	Holweg et al. (2018); Modig and Åhlström (2012); Pound, Bell and Spearman (2014)	Textbooks often lack real-world examples, focusing on illustrative situations instead.
Operations Management and Operations Research Teaching	• Case studies see widespread use within teaching applications.	Dobson and Shumsky (2006); Lapré (2010)	Identifying case studies requires examination of disparate literature.
Operations Management Practice	• Helps practitioners understand fundamental industrial problems such as the management of cycle times, queues, throughput and capacity to enable the improvement of process flow	Afy-Shararah and Rich (2018)	Disparate and varied empirical examples make it challenging for practitioners to understand application.

Table 1: Relevance of Little's Law to Areas of Operations Management

The paper proceeds by detailing the method adopted in the paper. This is followed by the main findings from the systematic review process. The outcomes from this then inform a number of vignettes highlighting interesting empirical applications. The versatility of Little's Law is then drawn out through the discussion before conclusions are provided.

2. Method

The method adopted in this paper comprises of two phases. The first phase is based on a systematic literature review. Through coding the papers and categorizing them on a framework, an overview of the literature was obtained. This phase also included defining the labels and boundaries of the different clusters. To gain further insights, a second phase with snowball sampling was adopted to identify further research papers to complement the review. This time, synthesis was based around qualitative vignettes. The vignettes provide more detail than can be

achieved purely from coding, yet condense the key details of the papers into a format for ease of understanding. This second phase confirmed that there was consistency within the clusters and consequently enabling a better insight into the versatility of Little's Law. From this, four factors contributing to versatility were identified, through the discussion presented in section 7. The method used in each phase is now described in more detail.

2.1 Phase 1: Systematic review and coding

The starting point in this phase was a systematic literature review to examine the empirical applications of Little's Law in the context of OM. Systematic literature reviews are important in OR and OM, in mapping and consolidating current theory as well as informing future research (Singhal and Singhal 2012, Seuring and Gold 2012). Given the development of Little's Law and its transfer between disciplines, the research is based on a keyword search of the online databases for the five main publishers of journals in OR and OM: Elsevier (through their ScienceDirect platform), Emerald, Informs, Taylor and Francis and John Wiley. Such a sample also covers discipline specific journals, such as those relating to healthcare. With systematic reviews, there is a methodological trade-off between a broad search of journals where the field of interest is narrow, and a smaller selection of journals for wider ranging topics (Suri and Clarke 2009; Seuring and Gold 2012). Because of the focus upon Little's Law, this could be considered as a narrow area of interest and therefore a broad search frame was adopted. No start date for the sample was specified, with the results including all articles published up to the end of 2017.

The systematic review process saw the identification of relevant research before selecting appropriate studies for further analysis through data extraction and synthesis. A summary of these stages is shown in Table 2. To identify the relevant research, the search term 'Little's Law' was combined with each of the following OM oriented search terms ('Production', 'Logistics', 'Supply Chain', 'Warehousing' and 'Inventory'). These were applied in each of the aforementioned databases, with the search tool looking through the full text. The result of this initial step yielded 992 papers. By just using this phrase, any of the extensions to Little's Law, such as the distributional form, would be captured. This was then further refined by searching within the full text for at least one of the OM search terms (for example, some papers had no relation to OM but cited publications from the journal Naval Research Logistics), and also removing non-research papers (such as book reviews). This reduced the sample to 717 relevant papers.

Inclusion/Exclusion criteria for the selection of studies	Elsevier	Taylor and Francis	Informs	John Wiley	Emerald	Total
Initial sample	405	269	187	99	32	*992*
Contains one of the filtering terms in main text	289	246	123	71	28	*757*
Is a research paper	283	242	103	62	27	*717*
Includes empirical examples	88	92	33	21	13	*247*
Uses empirical data	59	64	22	13	9	*167*
Uses Little's Law	42	43	18	9	4	*116*

Table 2. Summary of systematic literature review

Because of the focus on empirical applications, each paper was then examined in detail to determine whether there was an empirical element included. Two stages were considered. The first was to examine whether the research was context specific, as opposed to a generic model or discussion. A further consideration was if the paper used empirical data or not; this left 167 papers.

For data extraction, each paper was read in depth and coded. The coding process was designed to understand both the nature of the sample and the empirical applications of Little's Law. Table 3 provides details of the coding approach used in categorising the literature, as well as an explanation for the inclusion of the individual codes. The coding also revealed that a number of papers mentioned Little's Law (for example in the literature review) but then did not use it with the empirical data. These papers were also excluded, giving a sample size from the systematic review of 116 papers. The coding results were recorded in a table, representing the data extraction form. As Tranfield et al. (2003) state, it is a requirement to provide a full list of the papers on which the review will be based, and this can be found in the online supplementary material.

Code	Description	Reason for using
ID number	Identification number	To ensure all papers identified were coded.
Authors	Who wrote the paper	To identify any groups of papers by similar authors.
Year of publication	Year paper was published	To enable a longitudinal view of the sample to be made.
Journal	Journal of final publication	To identify any trends in where the research was published.
Cluster	In which cluster from Figure 1 is the paper positioned?	For theory matching to Figure 1.
Variable definition	What meaning was given by the authors to L, λ and W?	To examine what Little's Law was actually used to calculate.
Calculated variable	Which variable (L, λ and W) was calculated in the research?	To examine how the Little's Law equation was constructed
Use of Little's Law	Brief description of how Little's Law was applied in the research	To give some additional information on use to identify trends within clusters
Empirical application	Brief description of the empirical setting	To identify empirical transferability, and included detail on industrial setting and application.
Approach taken	In what way has Little's Law been used? Five possible codes were used: • Part of model – Little's Law within a wider mathematical model • Cross-check – to ensure that Little's Law was holding between observed variables • 'Rough cut' design – from two available pieces of data, give an approximation for the third variable • Diagnostic – similar in approach to 'rough cut' design, but used for analysing existing systems • Not used – where a detailed review identified that Little's Law was not actually used.	To distinguish between different research approaches.
Notes	Any other comments	To capture additional information not included in the codes that could be useful in the research.

Table 3: Coding criteria used in systematic literature review

2.2 Phase 2: Snowball sampling and vignettes

Recognising that the systematic process may not yield all relevant articles (Aveyard 2014), a snowball sampling approach was adopted to identify additional articles. This approach is recognised as giving greater depth to systematic reviews (Greenhalgh et al. 2004) and, when combined with a systematic review, is not considered 'haphazard' (Aveyard 2014). We revisited the reference list of the 167 papers that included empirical data and identified additional articles which helped to inform the research questions in section 1. The snowball approach identified 32 papers of potential interest to the study. A search of databases not aligned to a specific publisher (such as Ovid and Scopus) was also carried out. The additional articles from both these steps were reviewed and a further twelve papers added to the sample from the systematic literature review. As with the other papers, these all feature Little's Law in an OM context and make use of empirical data. The final sample size is therefore 128 papers.

To assist in data synthesis through providing brief but detailed illustrations of OM applications for Little's Law, and complement the more positivist findings from the coding, a series of vignettes were developed from papers in both the systematic and snowball samples. In analysing qualitative research, vignettes are a '…display technique with focused descriptions of representative or emblematic cases presented in narrative form' (Pendleton et al. 2002), and were used to utilise 'the force of example' (Flyvberg 2006). Vignettes can be used to provide representative snapshots, portraits or composites of events or categories in order to stimulate reflection and analysis of phenomena (Spalding and Phillips 2007). They have been used across a wide range of disciplines, including anthropology (Blodgett et al. 2011), education (Wolf-Wendell and Ward 2006) and gender studies (Holland 2008). Applications in OM tend to be as part of survey instruments for behavioural operations (Croson et al. 2013) rather than as a means for presenting research findings.

The vignettes produced give short summaries of particularly interesting papers generally no more than one page long and containing the key points and connections to the categorization framework. Hence vignettes were selected to offer 'useful variation on dimensions of theoretical interest' (Seawright and Gerring 2008). As such, they represent an intermediate stage in the analysis process although sample vignettes can be incorporated into the final write up of the research (for example, Amabile et al. 2001; Caudle 2004). Papers for development were selected in two ways. Firstly, as papers were reviewed during the coding process, we identified those that appeared to be particularly interesting given the research question. Vignette

summaries were then drafted reflecting the application of Little's Law in the paper(s) and highlighting aspects that were felt to reflect versatility. Upon completion of the coding, these papers were then compared to the others within each cluster to identify other papers of interest for the development of vignettes. Samples of vignettes developed can be found in the online supplementary material.

In evaluating the versatility of Little's Law through data synthesis, evidence was drawn from both the vignettes and coding of the sample. The vignettes provided detail on each application while the coding was used to consider whether the application was more widely generalizable across a broader range of papers. This approach avoids both information overload through having detailed notes on each paper and a lack of contextual information that can be evident from just relying on the coding itself. Through the synthesis of this combined evidence base, factors behind the versatility of Little's Law were identified. Reflecting this approach, we follow the advice of Erickson (2011) in presenting the vignettes, where they are combined with a more general overview of each cluster to show how typical/atypical the vignettes are.

3. Systematic Review Results

In terms of the industrial sectors represented within the literature sample (Table 4), semiconductor manufacturing dominates. It is clear that this manufacturing process is well suited to OR modelling and consequently provides much empirical understanding. While approximately 75% of the papers consider manufacturing operations, there are also examples from the service sector where healthcare is the both dominant and recently emergent, all the examples dated 2005 or later.

Sector		Number of articles
Manufacturing	Semiconductor	27
	Automotive	18
	General manufacturing	9
	Spare parts/remanufacturing	7
	Electronics	6
	Aerospace	5
	Apparel	4
	Other (manufacturing)	19
Sub Total		*95*
Service	Healthcare	15
	Logistics and Transport	9
	Computing	3
	Other (services)	7
Sub Total		*34*

Note: One paper featured two sectors, hence the total = 129

Table 4. Industrial sectors identified via literature sample

Table 5 considers the way in which the variables from Little's Law have been defined. As can be seen, all three variables have a range of definitions, depending upon the nature of the application and the availability of data. While definitions consistent with the OM interpretation of Little's Law by Hopp and Spearman (2008) are most common, there are variations for all three variables.

L		***λ***		***W***	
Definition	**Frequency**	**Definition**	**Frequency**	**Definition**	**Frequency**
Inventory	99	Arrival	57	Throughput time	46
Queue length	13	Throughput	57	Cycle time	43
Capacity	11	Output	12	Waiting time	27
Backorders	7	Not stated	8	Lead time	20
Order size	2			Not stated	1
Not stated	2				

Note: 6 papers provided more than one definition for at least one variable

Table 5: Definition of Little's Law variables

Finally, the 128 papers were coded against the framework shown in Figure 1, with definitions for terms used provided in Table 6 and details as to the papers contained in each cluster presented in the online supplementary materials. This categorisation was developed by the research team, having recognised the challenge of comparing, for example, a large-scale supply chain redesign project with a piece of work to design a production control system for a workstation. Given the first research question on demonstrating transferability, it was important

to for the framework to capture the nature of the different decisions to which Little's Law was being applied. This framework would also allow the identification of suitable papers for development into vignettes to explore the issue of versatility. One categorisation approach often used is to consider the level of application, as these will have different characteristics and scope (Earl 1994). An alternative approach is to consider the time scale of a decision window such as short, medium or long term; such terminology is commonly used in OM literature and textbooks. We combined these two elements, reflecting that there may be more than one time frame to decisions taken at each level.

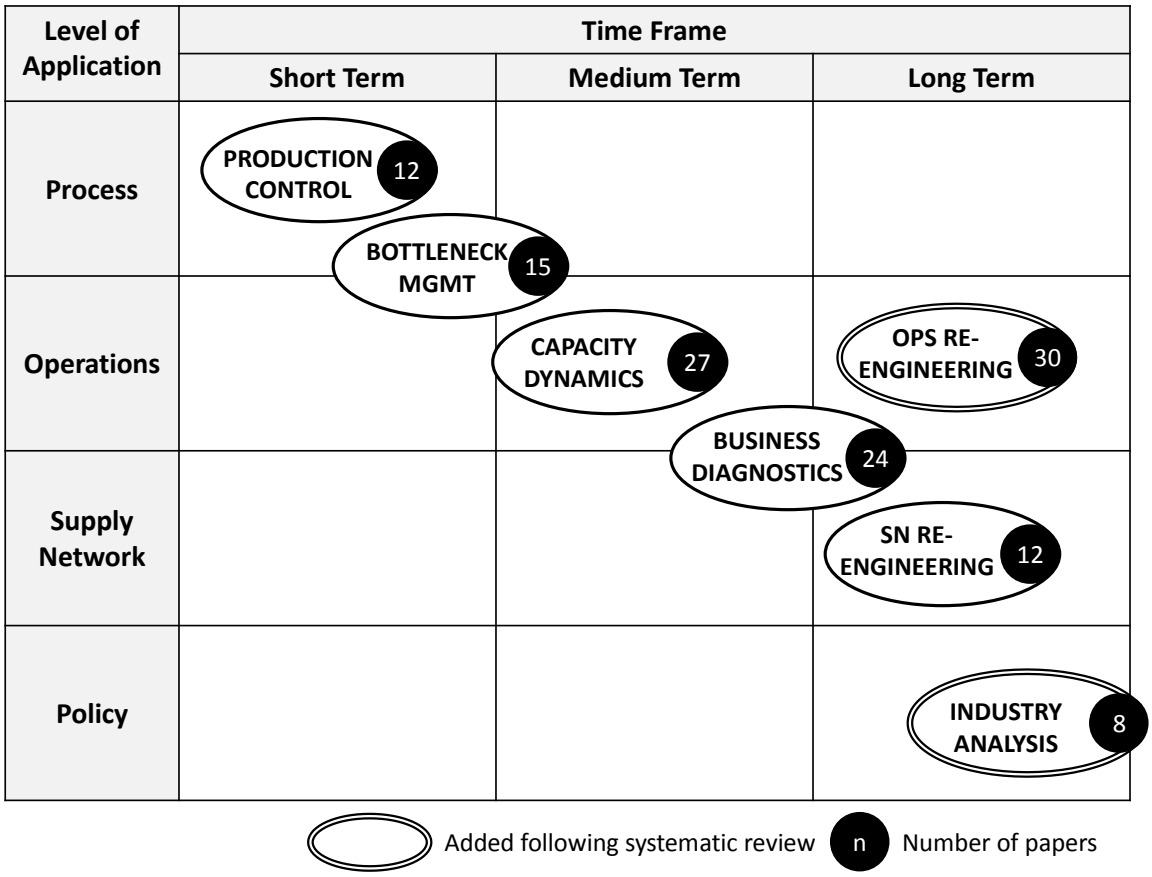

Figure 1: Mapping empirical applications of Little's Law

Term	Definition
Level of Application (based on Slack et al. 2016)	
Process	Decisions related to a network of resources connected by the flow of goods or services.
Operation	Decisions related to a set of processes, typically involving teams and a range of resources.
Supply Network	Decisions related to networks of operations, connected by the flow of goods or services.
Policy	Decisions considering multiple supply networks, either within or between different industrial sectors.
Time Frame (based on Fordyce et al. (1992)	
Short term	Next day to six months.
Medium term	A few months to two years.
Long term	Six months to seven years.
Categorizations (inductively derived from literature review)	
Production Control	Related to process tasks, and the research would inform decisions taken every planning cycle, possibly over a timescale of days and weeks. There is an emphasis on optimising scheduling decisions.
Bottleneck Management	Relate to either operation or process level concerns, by seeking to inform production control through identifying constraints or WIP related issues.
Capacity Dynamics	Related to operation level decisions taken across planning cycles, possibly over multiple weeks and months, and concerned with optimising current capacity and resources.
Business Diagnostics	Related to activities involving the analysis of historical data to achieve a 'snapshot' of performance at a particular time.
Operations Re-engineering	Related to re-design efforts across an operation, to determine major investment decisions. These decisions would likely be implemented over months and years.
Supply Network Re-engineering	Related to significant re-design efforts, typically applied across the supply network. The main focus is determining major investment decisions which would likely be fixed over months and years.
Industry Analysis	Related to analyses that benchmarked performance between multiple supply networks or industries to provide sectoral level insights or support policy making behaviour.

Table 6: Definitions of framework terms

Early scanning of some papers in the literature review, and their mapping against the framework, started to highlight some emergent clusters within them. Therefore, these clusters were used as the basis for categorizing the remaining papers, with naming terms reflecting the content of the papers included in each category (Production Control, Bottleneck Management, Capacity Dynamics, Business Diagnostics, and Supply Network Re-Engineering). Having attempted to

cluster all the papers, two additional categorizations emerged (Operations Re-Engineering and Industry Analysis) and these were added to the framework, along with an additional level of application. As noted earlier, each cluster is defined in Table 6 for clarity.

In terms of the spread of papers, it can be seen that there are examples of empirical applications across the full range of the framework. This begins to highlight the empirical transferability of Little's Law within OM. Capacity Dynamics and Operations Re-engineering are the most prevalent areas, with many papers in the former looking to establish WIP targets that then determine production plans (for example Yang, Fu and Yang 2007). The latter category focuses upon changing processes to improve performance measures linked to one of the three variables – typically inventory (Johri 1991), throughput rate (Chakravorty and Hales 2016) or time (Perona et al. 2016). It is also clear that the majority of papers are at the operations level. This may be explained by Little's Law being particularly applicable to medium and long term averages, while on a day by day basis there may be more variability. There is no significant evolution in the research over time, although those papers on Supply Network Re-engineering are generally more recent, with reflecting wider developments in OM focusing on supply chains.

From a sectorial perspective, those papers from the semiconductor industry are generally focused on Production Control, Bottleneck Management and Capacity Dynamics (21 out of 26 papers). This aligns with the modelling approach often taken in these papers. By contrast, the automotive industry has seen a greater focus on diagnostics and re-engineering (13 out of 17 papers), reflecting a stronger emphasis on process improvement possibly driven by the lean agenda in the sector. A similar focus is also found for healthcare research, with 14 (out of 15) papers in this area. Interestingly, these tend to adopt a 'rough cut' application rather than relying on an exact answer, as might be found in simulation or analytical modelling; an example here is Lovejoy and Desmond (2011).

4. Vignettes of OM applications

A sample of vignettes is now presented to demonstrate in more detail the versatility of Little's Law, the structure of this section reflecting Figure 1. These are derived from papers in both the systematic review and snowball sample. While noting that the selection is purposive, such an approach is consistent with the definition of vignettes provided earlier (Pendleton et al. 2002) and other research that has used vignettes in the analysis (Amabile et al. 2001).

4.1 Production Control

Cochran and Chen (2002) and Chen and Cochran (2005) identify a requirement for selecting appropriate decision rules for driving daily production plans controlling material flow in the context of semiconductor manufacturing. Such plans have to take into account status inputs on individual components, workstations, WIP, and customer demand, and details of how much work should flow through the factory. As they remark, the longer the cycle time, the more complex the production processes, and the greater the demand volatility, the more need there is for a daily plan to smooth WIP deviations from optimal. Their solution is to compare the outputs from three competitive plans based on Line Balance, On Time Delivery (OTD), and Bottleneck Utilisation Principles respectively. They are each assessed, for a range of possible scenarios via WIP Levels; OTD; and Bottleneck Loading performance metrics. Their study enables recommendations as to which algorithm is best and under what circumstances. When used for Line Balance the target WIP at each stage is determined via Little's Law:

$$\text{WIP} = \text{Throughput rate} \times \text{Cycle Time}. \tag{1}$$

It thus plays a key role in setting the WIP goals for each phase of production. As used by Chen and Cochran (2005) it essentially ties together the required throughput rate to the cycle time at each stage. They recommend that the cycle times used in each calculation be based on historical data; or alternatively be estimated from the theoretical times multiplied by a suitable factor for the individual process type as determined from factory records. Throughput rates are related to customer demand, and allow for factors such as current yield losses. Bringing these throughput rates and cycle times together via Little's Law enables the WIP goal to be set for each process. It can then be further exploited in estimating the total WIP effectiveness across all operations for a given daily manufacturing plan. Note that the flexibility envisaged by Chen and Cochran (2005) as the algorithms may be exploited operationally or tactically. Either the same pre-selected 'best algorithm is run daily and its outputted plan implemented or, in particularly dynamic situations, all three algorithms may be run, and the manufacturing team then selects the most appropriate plan for auctioning that day.

A feature of all of the papers represented within this cluster is the design of a production and inventory control system that meets a firm's performance objectives. Like Chen and Cochran (2005), inventory (Fordyce et al. 1992), service level (Berling and Marklund 2013; 2014) and utilisation (Kalir 2007) are the main objectives to be met, although Jeong, Kim and Lee (2001)

consider flow time. The definition of *L* in this cluster is WIP for all of the papers except those by Berling and Marklund (2013; 2014) who instead consider backorders and Zhang, Bard and Chacon (2017), where queues ahead of the process are calculated. All papers adopt a modelling based approach to system design, except for Riezebos (2010) who develops a POLCA system.

4.2 Bottleneck Management

Cycle time is a key performance measure in semiconductor manufacturing; yields are highly variable, so the shorter the cycle, the earlier process feedback can take place. Furthermore, long cycle times mean more chance of wastage, product contamination and deterioration. Given that cycle time is linked to WIP by Little's Law, Lozinski and Glassey (1988) propose the design and exploitation of a Bottleneck Starvation Indicator (BSI). Its purpose is to ensure that WIP is constrained at the bottleneck to minimise stock-outs yet excessive build-ups are also prevented. Hence, manufacturing personnel are alerted when upstream action is urgently required to ensure bottleneck process WIP is adequately constrained. The BSI is usually a graphical display of expected WIP at the bottleneck process predicted against the number of days ahead from current product flows from preceding workstations. The latter information uses Eq. (1) to estimate expected WIP for the system as a whole, rather than the process perspective in Chen and Cochran (2005).

The purpose of the BSI is to give the manufacturing personnel a simple display showing the risk of starvation, when it is to be expected, how much WIP is above/below target, and where the material is that is needed to keep the station from starving. By observing this graph of expected WIP as a function of 'time to reach bottleneck', under- and over-shooting of the target can be predicted as inventory is forecast to move down to the bottleneck. Appropriate action is then taken upstream to either avoid starvation or excessive clumping of inventory as needed. The necessary changes to scheduling can of course be computerised and output as recommendations which take into account up-to-date demand and yield information. By minimising the risk of bottleneck starvation, BSI makes a contribution to reducing semiconductor total cycle time and thereby enhancing productivity.

The papers contained within this cluster demonstrate that issues around bottleneck management are found across a wide range of industry sectors, with general manufacturing (Chhaochhria and Graves 2013), semiconductors, automotive (Nyhuis and Vogel 2006), electronics (Sheu and Chen 2008) and aerospace (Srinivasan, Ebbing and Swearingen 2003) all featuring. Like

Lozinski and Glassey (1988), Lin et al. (2008) also provide control charts to monitor the bottlenecks while the remaining papers tend to focus on the planning phase only. As with the Production Control cluster, the use of modelling approaches is commonplace.

4.3 Capacity Dynamics

When controlling job shops with wide ranging product portfolios Wiendahl and Breithaupt (2000) identify a number of reasons why it is insufficient to use only WIP control:

- The individual process time required for different components may vary considerably
- Variable product routings can lead to disparate machine loading patterns.
- The batch sizes necessary to best satisfy customer demand will range widely both over products and over time.
- Rush jobs, cancellations, and other disruptions such as equipment breakdowns need to be coped with.

A multi-loop control system was proposed by Wiendahl and Breithaupt (2000) to counter these challenges. It has both a WIP controller and a backlog controller. These interact to adjust capacity in order to eliminate backlog via maintaining WIP within bounds about its target value. To enable operation in the job shop, it is necessary to establish the logistics operating curve relating WIP, lead time and performance. These must contain realistic estimates of the delays (typically between 1 and 5 days) incurred when changing capacity via such actions as authorising overtime or altering shift patterns. It must also allow for the effect of changes in input orders on shop throughput rate and hence the anticipated impact on WIP.

Little's Law for this application is written as the order based equation;

$$\text{WIP [order]} = \text{Mean arrival rate} \times \text{Mean lead time} \tag{2}$$

Since the purpose is to control a jobbing shop, within the control system this is re-written in terms of the work based funnel formula;

$$\text{WIP [work]} = \text{MPER [w]} \times \text{MR} \tag{3}$$

where MPER [w] is the mean performance in hours of work achieved per shop calendar day and MR is the mean completion time of the work centre in calendar days. Thus Wiendahl and

Breithaupt (2000) argue that conceptually the WIP controller is input-facing (concerned with incoming orders) whereas the funnel formula is output facing since it concentrates on work required to deliver finished goods.

Simulation predicted results from this design were subsequently published in Wiendahl and Breithaupt (2001). Based on actual order patterns for an automotive components supplier working with lot sizes varying from 5 to 5000, they output a backlog reduction potential of over 90%, forecast to be achieved over a 60 calendar day period.

While the previous two clusters have had a degree of consistency between the papers, there is more variety for those considering Capacity Dynamics. Research has considered a greater range of production environments, and especially make-to-order and engineer-to-order situations (Arashpour et al 2015; Ben-Gal, Braha and Maimon 1999; Pinilla and Prinz 2003; Whitney 1985, Yuan and Graves 2016). There is also a small group of papers that examine issues around the management of spare parts. Diaz (2003) and Wang, Cohen and Zheng (2002) use Little's Law in the calculation of delay time (W) for a given inventory level, while Kranenburg and van Houtum (2007) calculate the stock level required (L) for a given service time.

By focusing on capacity, it may be the case that the resources required vary depending upon the product. Both Arashpour et al. (2015) and Chen et al. (2012) identify the skill levels of workers as important, and therefore include adjustment factors in the Little's Law calculation that take this into account. In terms of performance objectives, these are consistent with the earlier clusters with metrics such as inventory, lead time and utilisation. However, Gong et al. (2013) and Yuan et al. (2017) use Little's Law as part of a model to maximise revenue in the self-storage warehousing industry.

4.4 Business Diagnostics

Running a semiconductor factory is complicated due to many interacting factors. There may be up to 500 discrete processing steps, up to 10 major fabrication process flows in a facility with 400 pieces of equipment operating 24/7 (Dabbas and Chen 2001). Hence investment in expensive Computer Integrated Manufacturing (CIM) systems to track lots-in-process and manage equipment preventive maintenance programmes is commonplace. There is an inherent need to clean-up vast amounts of data, rationalise and integrate it to provide a data base for effective controls. According to Dabbas and Chen (2001), the controls are based on the four

major areas of Line Balance; Cycle Time; On-Time Delivery; and Bottleneck Reports. These are broken down according to products, lots, equipment, processes etc. In their research, the goal is to improve performance of the factory in both the short and long term with CIM playing the pivotal role. Little's Law appears frequently within the line-balance cycle times, and WIP targeting software. As with Lozinski and Glassey (1988), Eq. (1) is used at a system rather than product level.

Much attention is paid to both actual (present and trend) and minimum cycle times as triggers for process improvements. At the workstation level visual 'Mountains of WIP' displays of actual and expected values are provided so that managers quickly identify problems and take appropriate action. Furthermore, if over a period of time target and actual remain in close agreement then line balance is good. The CIM software also exploits the use of Little's Law in quasi control charts covering complete process pathways and for 'WIP flushing'. The above formula is modified to present a metric of WIP effectiveness which is realistically targeted at 85%. By also computing WIP effectiveness for the two special cases where firstly only positive deviations, and secondly only negative deviations are included it is possible to superimpose further guidelines on WIP control charts. These enable managers to see at a glance to what extent the factory may be short of WIP or awash with WIP, and the rate at which there may be a future build-up or leakage.

The papers within this cluster can be subdivided into three main groups. The first, like Dabbas and Chen (2001) use a wider model to evaluate the performance of a system. Examples include Gung and Steudel (1999) and Narahari and Khan (1996). The second group uses Little's Law to give an approximation for one of the variables when the other two are known. Often this relates to the average time an activity takes as this can be difficult for organisations to record. Both Hyer, Wemmerlöv and Morris (2009) and van der Vaart, Vastag and Wijngaard (2011) use this to calculate the time an average patient spends in hospital, while Larson, Ghaffarzadegan and Xue (2014) estimate the length of tenure for academics. An important aspect here, and one illustrated by Walsh, Sawhney and Bashford (2007) is that these are long term averages. The final set of papers (including Dinis-Carvalho et al. 2015 and Baysan, Durmusoglu and Cinar 2017) present visualisation techniques for firms to evaluate their performance. All three groups cover a wide range of manufacturing and service applications.

4.5 Operations Re-engineering

While modelling is often used to inform process improvements, one of the challenges that can be faced is getting non-specialist management to understand how the models work. The simplicity with which Little's Law can be understood aids this process. Harris (2010) demonstrates this in the context of healthcare, with additional commentary on this case being provided in Little (2011). Harris himself is a practitioner working for TeamHealth, designing staff scheduling systems for Emergency Departments (EDs). While final decisions are based on complex modelling, Little's Law provides an approach for 'rough cut' capacity planning, and in a form that senior management can comprehend.

Like many other production systems, the process flow of each item (the patient) through an ED can vary significantly, depending upon whether they are treated there or sent to another department, the people that are needed to treat them and any other processes that need to occur (e.g. x-ray). However, an important performance measure is the length of stay (LOS), which gives an indication of resource use and patient progress towards recovery. Therefore, Little's Law can be expressed as:

$$\text{Length of Stay} = \text{Number of Patients in Process}/\text{Arrival Rate of Patients} \qquad (4)$$

This equation can then be used either to measure the length of stay of patients or to calculate the staffing level needed to achieve a target LOS. It is in this latter context that Harris (2010) discusses the application of Little's Law, and both at the system level and also for categories of staff (such as physician, nurse). By knowing the average number of patients in process and the productivity of staff, an initial figure for staffing levels can be calculated. However, because of variability in the system and the negative impact of high resource utilisation on the time spent in a system, this should be considered a minimum, to which Harris (2010) suggests a 10-20% increase based on his experience.

The 'rough cut' approach espoused by Harris (2010) can be found within half of the papers in this cluster. The emphasis is on improving the flow of items through a process, be these croissants (Liberopoulos and Tsarouhas 2002), vehicle components (Colledani et al. 2010), patients (Howell 2011) or legal cases (Zuniga and Morillo 2014). The alternative approach taken by papers in this cluster is modelling and simulation, where future state scenarios are evaluated in a test environment. In most cases, the focus is again on flow through the process,

with time a key metric, an exception being Cohen (2010) who uses service level as a measure in relation to a technical support team. Although focusing on flow, Bartholdi and Gue (2000), Song and Woo (2013) and Mishra, Roy and van Ommeren (2017) model facility layouts.

4.6 Supply Network Re-engineering

A particularly noteworthy example here is Guide, Muyldermans and van Wassenhove (2005). They applied Little's Law to make the case for substantial re-engineering of the Hewlett Packard reverse supply chain for Notebook computers. Low management priority was accorded to this chain, refurbishment times were long, and queues throughout the system were substantial and increasing. The upshot was that the financial return for these remarketed products was much less than it should have been. This was in part due to a failure to understand the price-time sensitivity of the product on resale. Of particular interest to us is that Guide, Muyldermans and van Wassenhove (2005) exploited the application of Little's Law to make the case for substantial re-engineering (and prioritisation) of the Hewlett Packard reverse supply chain. It was exploited in the form;

$$\text{Renovations Lead Time} = \text{Returns WIP}/\text{Throughput Rate} \tag{5}$$

The investigators found that although masses of data existed, it was disconnected and needed much transformation into usable form. Little's Law played a prominent part in establishing realistic lead times for the outsourced supplier used for the refurbishment of returned items. Hence via simple curve fitting to cumulative arrival and exit shipments Guide, Muyldermans and van Wassenhove (2005) estimated a typical delay of 2.6 months, a process flow rate of 1000 units/month and, inevitably, WIP of 2600 units. To this must be added the 1 month unrefurbished ('Goods In') warehouse delay and the 1.4 months refurbished ('Goods Out') warehouse delay. This sums to a total of 5 months to which must be added any logistical delays and travel times outside this part of the remarketing SC. Hewlett Packard cost data showed that during this period the value of the refurbished Notebook could drop in value by 20%. Indeed such cumulative delay might lead to write off due to obsolescence. Fortunately in this case Little's Law has played a detective role in providing ball-park evidence supporting the case for root-and-branch re-engineering of a major reverse supply chain in which price-time sensitivity has a major impact.

The papers within this cluster can be categorised in the same way as for Operations Re-engineering, with half the papers using Little's Law to estimate measures and the remainder using modelling. The difference from the previous cluster is the focus across a supply chain rather than just within a single operating unit. For example, Alfonso-Lizarazo, Montoya-Torres and Gutiérrez-Franco (2013) estimate key parameters for a closed loop palm oil supply chain, Kerbache and MacGregor Smith (2004) use Little's Law in Mean Value Analysis calculations when modelling a suitcase supply chain and Jónasson, Deo and Gallien (2017) consider the allocation of clinics to HIV testing laboratories.

4.7 Industry Analysis

Richard Schonberger has contributed widely to the practice of organisational benchmarking, particularly in comparing Japanese and Western manufacturers efficiencies and effectiveness. His database contains some 1,350 graphs depicting the success or otherwise in the application of lean based improvement programmes. However in his two 2011 articles (Schonberger 2011a, 2011b) he makes it clear that the same ideas can be used to highlight the need for change more widely than just a general wake up call. Firstly such benchmarking need not be restricted to production, but can be applied to the range from individual processes to extended supply networks or even comparisons between similar organisations at an industry level. Secondly, the methodology is equally applicable to sectors other than manufacturing. What is less obvious, at first sight, is that the Schonberger preferred performance measure of Annual Stock Turns (AST) exploits Little's Law in its estimation from readily available data.

He reasonably assumes that inventory is either reliably recorded or can be counted. Furthermore that throughput is similarly available. Dividing inventory by throughput gives the estimate of lead time, whence inversion yields AST. In seeking generality, Schonberger (2011a) advocates the use of relevant financial equivalents for both inventory and throughput. Thus his application of Little's Law yields;

$$\text{Annual Stock Turns} = \text{Value of throughput}/\text{Value of inventory} \tag{6}$$

Note that, value is taken as a monetary term (in this vignette, dollars) and because of the focus on stock turns rather than actual inventory levels, the equation is the inverse of Eq. (5).

Having estimated AST according to this formula Schonberger proceeds to give examples covering a wide range of performance, both improving and declining, and due to a number of causal relationships, some predictable, such as due to the start up of a new business process improvement programme, but others unexpected, such as a drop in quality resulting from a particular batch of raw materials. These include Walmart, Toyota, Hormel Foods, Federal-Mogul, and Cooper Industries. In some cases the improvement progresses smoothly, but in some cases it is quite turbulent both in magnitude and frequency. Schonberger also switches between data for the organisation and constituent time series involving WIP, finished goods, and purchased materials. Although the commentary may be at the supply network level, the purpose is to benchmark between these different networks.

This cluster of papers has seen a growth in recent years, with five of the eight papers being published between 2013 and 2015 inclusive. Interestingly, these five papers also use modelling (mostly statistical, except for Pierson and Sterman (2013) who use system dynamics); the earlier papers only use Little's Law to estimate values. The panel data always considers multiple supply networks and comes from a variety of sources including government (Klassen and Menor 2007; Georgantzas 2003), industry bodies (Bennett 2013), financial databases (Lee, Zhou and Hsu 2015) and academic studies (Morita et al. 2015). Often, data from several sources is combined in the research.

5. Discussion

The above systematic review and vignettes begin to highlight that Little's Law has a high degree of empirical transferability and versatility within OM, in terms of the nature of the application and the industrial sector within which the empirical work is undertaken. This range of uses builds on the universality of its application within OR and reinforces the perception of it as a 'law' of OM. By contrast, from the sample of papers selected, there was no evidence of the distributional form of Little's Law being used, which may reflect the constraints on its generalisability highlighted earlier. The following discussion aims to develop this more fully, drawing on comparisons both within and between the clusters in Figure 1. In doing so, we also reflect on alternative approaches to those highlighted through the analysis.

One suite of applications relates to planning and scheduling operations within a production system (either of a physical product or a service). This encompasses the Production Control, Bottleneck Management and Capacity Dynamics applications. Many of these types of

application are based on OR modelling approaches. The vignettes highlight applications in terms of WIP control, identifying bottlenecks and workload control, reflecting many studies in these areas. While most focus on the products, an interesting variation is Arashpour et al. (2015) where 'workload' as activity levels for construction workers. However, other applications include production scheduling (Jeong, Kim and Lee 2001), card-based production control systems such as Kanbans (Black 2007) and POLCA (Riezebos 2010) and warehouse capacity planning (Gong et al. 2013). These systems need not be applied just to flow-based production lines, with job shop and flexible manufacturing systems also featuring (Whitney 1985; Ben-Gal, Braha and Maimon 1999; Wiendahl and Breithaupt 2000). Another feature of this research is that there is often a hierarchy of decision making, with information from one level informing another. This can be seen in papers such as Wittrock (1992) and van Daele et al. (2008). As noted earlier, Little's Law can apply to the system as a whole or individual sub-systems and the hierarchy of information flows evident in the literature reinforces this. While Little's Law connects three key variables for planning and scheduling, other 'laws' from OR can also be used such as Kingman's formula, which approximates waiting time depending upon utilisation, variability and service time (Hopp and Spearman 2008), or the Pollaczek-Khintchine formula which relates queue length (effectively WIP) to the service time distribution (Montoya-Torres 2006). Alternatively, the use of simulation tools rather than mathematical formulations may be appropriate.

Another aspect relates to the reporting and analysis of data. Little's Law has the potential to play an important part in the identification and analysis of performance metrics. This is particularly the case when key metrics are unavailable and some form of estimation is required. While this is more likely to link with the business diagnostics category, it may also be used at other levels. From the vignettes, Dabbas and Chen (2001) use Little's Law to help 'clean up' data relating to effective control and reporting, while Guide, Muyldermans and van Wassenhove (2005) also show that it can help to make disconnected and fragmented data more usable ahead of supply chain reengineering. This latter paper, along with Walsh, Sawheny and Bashford (2007) and van Hilst, Huang and Lindsay (2011) show the value of using cusum graphs to provide a visual depiction of inventory and time. Other papers from the systematic review that used Little's Law to identify performance measures include Hyer, Wemmerlöv and Morris (2009), van der Vaart, Vastag and Wijngaard (2011) and Simonetti et al. (2014). All of these sources are from the healthcare sector, which highlights the opportunities for using Little's Law in situations where significant volumes of data can exist. There are also some papers where

the data is used within a model to diagnose the causes of problems (such as Narahiri and Khan 1996; Li et al. 2007) or evaluate future scenarios (Alfonso-Lizarazo et al. 2013). With the advent of 'big data' and data science plus the future emergence of Industry 4.0, the need for Little's Law as a means to extrapolate performance data becomes less important. In addition, because the estimations are based on long term averages, there may be times when it is more appropriate to observe and collect all three values to capture the variability.

Further, the analysis of data using Little's Law can be used to inform benchmarking both within the context of diagnostics and also at a policy level. The vignettes based on Schonberger (2011a and 2011b) demonstrate the wide range of levels at which benchmarking may be conducted. This includes organisational, sector and cross sector benchmarking. Other authors who have also considered Little's Law in the context of benchmarking at firm or industry level include Benson, Cunningham and Leachman (1995) and Klassen and Menor (2007). However, some of these cases, the use of Little's Law is just postulated, and therefore opportunities exist to develop research in this area. Such approaches may complement more established techniques in, for example, finance.

Finally, the versatility of Little's Law is such that it can inform improvement activities at both the process and supply chain levels. Generally, such actions are informed by a diagnostic phase, as demonstrated through the Guide, Muyldermans and van Wassenhove (2005) vignette, Colledani et al. (2010) and Perona et al. (2016). It can also be included within general diagnostic approaches, often linked to lean principles (Obeidat, al-Aomar and Pei 2014; Dinis-Carvalho et al. 2015; Bertolini, Romagnoli and Zammori 2017). However, there are some papers where the diagnostic stage is not evident, particularly when creating 'new' supply chain structures (Nozick and Turnqvist 2001; Vanteddu, Chinnam and Gushikin 2011). Some of the textbooks that discuss Little's Law are focused on this broader process (such as Pound et al. 2014). More generally there is an established body of tools, methods and approaches for analysing operations (Salama et al. 2009), and Little's Law is just one tool that could be used alongside these.

6. Conclusion, Contribution and Future Research

The aim of the paper was to *identify, classify and consolidate* published empirical applications of Little's Law in a systematic manner to better understand its versatility. To establish the versatility of Little's Law in OM, two research questions were developed. The first asked 'Do the applications of Little's Law demonstrate empirical transferability to enable it to represent a

“law” of OM?’ Secondly, to develop a deeper understanding of how versatility enables this transferability, the question ‘What factors contribute to the versatility of Little’s Law in operations management?’ was posed to extract some common factors behind its use. Through a systematic literature review process and coding scheme, complemented by vignettes of noteworthy practice, 128 papers were identified and synthesised.

Figure 2 summarises the main findings to the first research question. In terms of industrial sector and level of analysis, the research has demonstrated a range of applications, and certainly more variety than that observed in the ad-hoc reviews. Much of the empirical research is based on semiconductor manufacturing, and therefore a need exists to develop further applications in other industrial sectors, with service oriented applications appearing to be a particular area for growth. The papers were also categorised to reflect the application of the research carried out. Seven distinct clusters of papers were identified, as shown on the vertical arrow in Figure 2. Three of these focused on the running of the production process across the short and medium timescales, while a further three considered diagnostics and re-engineering activities over the medium to long term. The final cluster took a long term perspective and enabled firm and industry level benchmarking to be undertaken. From this, we conclude that Little’s Law has empirical transferability in OM across levels, sector and time domains, and therefore meets the standard established by Micklethwait and Wooldridge (1996).

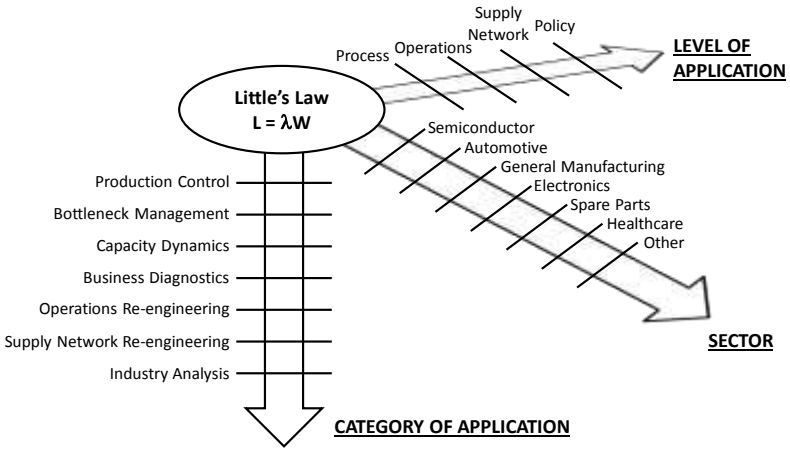

Figure 2: The empirical transferability of Little's Law in operations management

Turning to the second research question, Table 7 uses evidence from the coding and vignettes to identify four factors contributing towards the versatility of Little's Law in contemporary OM practices. Three of the factors draw to some extent on the usefulness of Little's Law within OR, albeit with an OM orientation, based on both the coding information and vignettes. The tautological nature of Little's Law from a mathematical perspective makes it applicable to many situations ('applicability') and many uses ('utility'), evidenced by the range of industrial applications and the variety of variable definitions. The ability to relate three performance measures ('simplicity') is also mentioned in Hopp (2008). The simplicity with which this can occur, and therefore be understood by management is probably best seen in the computer remanufacturing example (Guide, Muyldermans and van Wassenhove, 2005) in s5.6. Reflecting upon Table 7, similarities between the factors and the requirements for good theory proposed by Wacker (1998) emerge – clear definitions ('utility') and domains ('applicability'), relationship building ('simplicity') and theory predictions with empirical support (all three factors). By contrast, 'visibility' is derived entirely from the vignette based research, where Little's Law plays an active role in synthesising data into a format easily understood by managers.

Versatility factor	Rationale	Evidence
Applicability - Little's Law is applicable to a wide range of physical situations.	The variety of industrial sectors and production systems evidenced in the research.	Table 4 illustrates the range of industrial sectors, while Figure 1 shows the different levels. The vignettes also evidence different forms of industrial application, from large scale production (s4.1) to jobshop (s4.3)
Utility - Little's Law has a number of distinctly different uses.	The variables can be defined in a variety of ways.	The coding revealed a range of different definitions (Table 5), this variety being reinforced in the vignettes (cf. s4.3 against s4.7).
Simplicity - Little's Law relates three performance measures within a system; hence if two are known, the third may be estimated even when 'hidden'.	Many applications use Little's Law as an estimator of an unknown measure, while managers also find it easy to grasp.	A group of papers adopting a 'rough cut' design or diagnostic approach was found from the coding. The vignettes in s4.5 and s4.6 are particularly pertinent examples.
Visibility - Little's Law can form the basis of simply updated highly informative management displays.	Being able to present substantial or discrete data sets in a clear fashion underpins many of the pieces of research identified.	While not explicitly captured in the coding, the vignettes in s4.2 and s4.4 show how visibility can be provided.

Table 7: Factors enabling the versatility of Little's Law

6.1 Academic contribution

Table 1 identified a range of academic gaps which this paper addresses. The main contribution of this paper is to OR and OM theory, in that it is the first paper to systematically review the empirical applications of Little's Law. This compliments existing reviews of technical (non-applied) advances in Little's Law (Whitt 1991, Wolff 2011, and Little 2011) but additionally offers researchers and managers insights into the myriad means and uses in different contexts: its empirical transferability and versatility. Our study has also provides evidence that Little's Law passes the 'transferability test' posited by Micklethwait and Wooldridge (1996). Hence, it can be seen to represent a 'law' of OM, both analytically and empirically, and across a range of organisational scales from a machine to an industry.

The review also contributes to gaps in existing knowledge related to OM textbooks and OM/OR teaching. Both of these areas can benefit from the consolidation of empirical applications, providing real-world examples that can be used both to illustrate Little's Law and developed

into tutorial material to support learning. The synthesis and classification through the literature review recognises that the applications are not homogeneous in nature, and therefore enables users to identify the most appropriate examples for a given context.

6.2 Practical contribution

It was also identified in Table 1 that OM practice can benefit from this research and, as with the academic contribution, they can use the categorisation to identify research activities that particular match their needs. For those in practice with an OR background, they will probably be familiar with Little's Law but may not have considered the variety of OM modelling applications that it underpins.

By contrast, for operations managers, the principles behind Little's Law could be used in a 'quick and dirty' manner to judge performance – for example, during a shop floor walk around to identify how long stock is hanging around. Alternatively, a manager may be interested in undertaking a business process re-engineering exercise within their organisation as part of a lean transformation. Therefore, papers within the operations or supply chain re-engineering categories may provide ideas as to how to collect and visualise data to inform decision making.

Finally, an analyst may have been asked to compare inventory patterns between different organisations in a particular industry. The methods, and a demonstration of their applicability, may assist in enabling them to identify pertinent data that is not readily visible. For example, there are examples of how to convert financial measures to operations measures.

6.3 Future research

A number of future research opportunities have emerged from this research. Although there has been growth recently, there are still relatively few studies that utilise Little's Law to calculate or verify performance measures at an industry level (the Industry Analysis cluster). The ability to convert reported financial measures into average inventory levels, and then either undertake longitudinal or statistical studies to identify causes of variation appears a particular opportunity. Exploiting the opportunities that exist here offers an interesting future development in OM.

There also appear to be opportunities as a result of the 'rough cut' approach to using Little's Law in Business Diagnostic and Operations/Supply Network Re-engineering applications, especially by testing them in different industrial sectors. Such approaches are often easier to

understand by practitioners and, as demonstrated through Howell (2011), can offer good approximations of the impact from various interventions.

Finally, one of the issues with Little's Law is that it considers long term averages and therefore does not consider the impact of variability. Currently, modelling and simulation are the main methods to include this, particularly at operational and tactical levels in our framework. Hence, a research opportunity exists in identifying approaches that demonstrate the same versatility as Little's Law, and particularly ones that can be applied in the same 'rough cut' manner. The factors identified in this paper may prove a useful test in evaluating this. A starting point may be Kingman's equation, which is suggested by Hopp and Spearman (2008) and also features in Klassen and Menor (2007) and Li et al. (2007) although the *Factory Physics* based VUT (Variability, Utilisation, Time) Equation has also been used (Wang et al. 2015). However other approaches are used in the papers examined from the scientific (Nyhuis and Vogel 2006) to the experiential (Harris 2010). Determining the most effective would be an interesting focus for research.

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