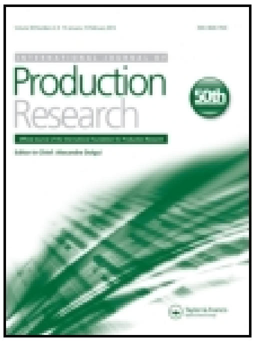

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Supply-chain uncertainty: a review and theoretical foundation for future research

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Supply-chain uncertainty is an issue with which every practising manager wrestles, deriving from the increasing complexity of global supply networks. Taking a broad view of supply-chain uncertainty (incorporating supply-chain risk), this paper seeks to review the literature in this area and develop a theoretical foundation for future research. The literature review identifies a comprehensive list of 14 sources of uncertainty, including those that have received much research attention, such as the bullwhip effect, and those more recently described, such as parallel interaction. Approaches to managing these sources of uncertainty are classified into: 10 approaches that seek to reduce uncertainty at its source; and, 11 approaches that seek to cope with it, thereby minimising its impact on performance. Manufacturing strategy theory, including the concepts of alignment and contingency, is then used to develop a model of supply-chain uncertainty, which is populated using the literature review to show alignment between uncertainty sources and management strategies. Future research proposed includes more empirical research in order to further investigate: which uncertainties occur in particular industrial contexts; the impact of appropriate sources/management strategy alignment on performance; and the complex interplay between management strategies and multiple sources of uncertainty (positive or negative).

Keywords: supply-chain uncertainty; supply-chain risk; supply-chain management; literature review; alignment theory; contingency theory

1. Introduction

Supply-chain uncertainty is an issue with which every practising manager wrestles (Hult *et al.* 2010), deriving from the increasing complexity of global supply-chain networks, which include increased potential for delivery delays and quality problems (Bhatnagar and Sohal 2005). As early as Davis (1993), it has been argued that such uncertainties, which 'plague complex networks', are a major problem and important to understand. However, in the intervening years, while there has been much research into specific sources of supply-chain uncertainty, either relevant to internal manufacturing processes, supply-side processes, or demand-side issues (usually end-customer demand); there are many other distinct sources of uncertainty which have received insufficient attention (Prater 2005). In addition, there is much recent interest in the related area of supply-chain risk (Ritchie and Brindley 2007, Braunscheidel and Suresh 2009, Neiger *et al.* 2009). Such authors have claimed that the repercussions of inadequate risk-management policies can have a severe impact on company performance; for example, Hult *et al.* (2010) list resultant losses for major companies including Cisco, Pfizer, and Boeing. Developing a better understanding of both uncertainty and risk therefore remains a pertinent problem in the current competitive market with the many new challenges that continue to unfold in this global and IT-driven arena.

In order to understand and research 'supply-chain uncertainty', it is first necessary to define it. Given that this term is often used interchangeably in practice with the term 'supply-chain risk' (Peck 2006, Ritchie and Brindley 2007), it is also essential to clarify how the two terms differ. Some authors in the literature make a clear distinction between the terms 'risk' and 'uncertainty' (e.g. Courtney *et al.* 1997, Hillson 2006), while others suggest that the distinction is blurred to the extent that it is not important to distinguish between the two (e.g. Juttner *et al.* 2003, Peck 2006, Ritchie and Brindley 2007, Li and Hong 2007). Where a difference is argued, a key reason relates to the type of outcome that might be expected. Some authors suggest that risk is only associated with issues that may lead

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to negative outcomes (Hillson 2006, Peck 2006, Wagner and Bode 2008); while issues of uncertainty can have both positive and negative outcomes. For example, the risks associated with a natural disaster can only lead to supply-chain problems; whereas uncertainty regarding customer demand can result in demand being either better or worse than expected. It can therefore be argued that the term 'supply-chain uncertainty' is broader, and can be used to encompass issues that have sometimes only been referred to under the risk banner. Supply-chain uncertainty then, as defined here, is a broad term that refers to uncertainties (including risks) that may occur at any point within a global supply-chain network. This definition of supply-chain uncertainty fits with that given by van der Vorst and Beulens (2002), who add further depth and clarity as follows:

> decision-making situations in the supply-chain in which the decision-maker does not know definitely what to decide as he [or she] is indistinct about the objectives; lacks information about (or understanding of) the supply-chain or its environment; lacks information processing capacities; is unable to accurately predict the impact of possible control actions on supply-chain behaviour; or, lacks effective control actions (non-controllability).

Having determined that both the uncertainty and risk literature are relevant to a study of supply-chain uncertainty, there is a timely need to undertake a review of the emerging literature, including the relevant aspects of both terms, in order to establish the current state-of-the-art and areas in need of further research. To date the reviews published have tended to either be broad – see for example the review of Supply-chain Management (SCM) by Burgess *et al.* (2006) – or focussed on other specific areas of SCM – such as performance metrics (Gunasekaran and Kobu 2007) and supply-chain flexibility (Stevenson and Spring 2007). While there has also been a recent literature review of quantitative modelling approaches under uncertainty (Peidro *et al.* 2009), no review has yet been published that looks at a broader set of approaches to the management of supply-chain uncertainty. In addition, although there has been a review of the supply-chain risk area (Juttner *et al.* 2003), this does not incorporate important contributions to the uncertainty literature or the more recent research in both areas. There has also not yet been an attempt to determine a comprehensive understanding of the many sources of uncertainty and how these can be aligned with management strategies in order to improve supply-chain performance, thereby developing theory in this area. Instead, previous research has tended to focus on the theory of the SCM paradigm in a broader sense (Chen and Paulraj 2004, Giannakis and Croom 2004); on supply-chain risk (Ritchie and Brindley 2007); or, on narrower aspects of uncertainty such as supply and demand uncertainty only (Lee 2002, Sun *et al.* 2009). This paper seeks to address these gaps by presenting both a literature review, including the identification of research gaps, and a theoretical foundation for future research in the supply-chain uncertainty area.

The remainder of this paper is organised as follows. Section 2 describes the research method, classifies the literature and establishes the need to first identify sources of uncertainty. Sources of uncertainty are then identified in Section 3 before Section 4 looks at the management of these sources of uncertainty. Section 5 presents a theoretical foundation primarily aimed at future empirical research which aligns supply-chain management strategies with sources of uncertainty; and which can be populated using the literature review material. Finally, Section 6 draws conclusions and suggests broad topics in need of future research.

2. Identifying and classifying the literature

The terms 'supply-chain uncertainty' and 'supply-chain risk' were the primary keywords used to search the business and management areas of three databases: ABI/INFORM Global (ProQuest); Business Source Premier (EBSCO); and Academic search complete (EBSCO). However, the term 'supply-chain uncertainty' alone identifies in excess of 20,000 papers, as it is used in many mathematical modelling papers as well as in conceptual and empirical studies. As the mathematical modelling papers have already been recently reviewed and tend to focus on a narrow set of uncertainties (Peidro *et al.* 2009), a comprehensive discussion of these papers is not included here. Instead this review focuses on conceptual and empirical studies. The review does not claim to be comprehensive in terms of the articles included as many discuss the same supply-chain uncertainty/risk issues, but aims to be comprehensive in identifying sources of uncertainty; management strategies and existing empirical evidence.

At the highest level, the literature can be classified in terms of whether it identifies sources of uncertainty and/or whether it presents uncertainty management strategies, as illustrated in Figure 1. Sources of uncertainty have been identified primarily by considering the various models of uncertainty that have been presented by previous authors; these models can themselves be categorised as also illustrated in Figure 1. Strategies for managing uncertainty partially come from the same literature sources, but also from other more discursive papers that focus on particular

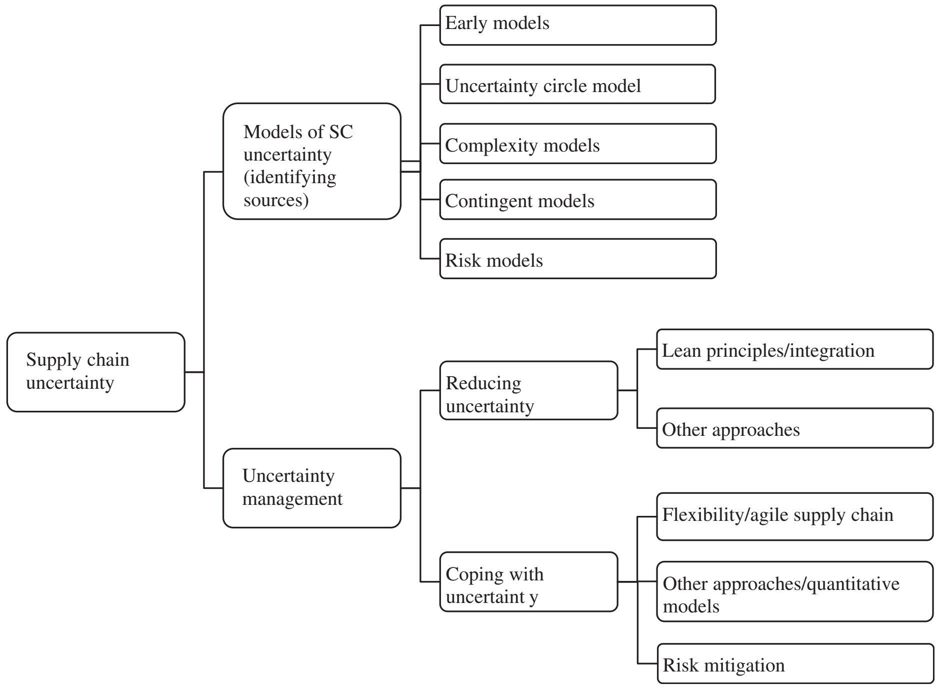

Figure 1. Uncertainty literature classification.

management approaches, such as supply-chain collaboration. This paper classifies uncertainty management strategies into two broad categories:

- Reducing uncertainty strategies: any uncertainty management concept that enables organisations to reduce uncertainty at its source. For example, applying a suitable pricing strategy or incentive may reduce customer demand fluctuation.
- Coping with uncertainty strategies: a strategy which does not try to influence or alter the source of uncertainty. Instead, it tries to find ways to adapt and hence minimise the impact of uncertainty. For example, to cope with customer demand fluctuation, organisations may develop advanced forecasting techniques that enable better prediction of demand and reduce forecasting errors. In this case, although demand uncertainty is not changed, better forecasting results enable organisations to anticipate variations in demand, thereby lessening the impact of the uncertainty.

A third concept similar to that of coping with uncertainty is mitigation, which refers to any action that may lessen the adverse effects of the outcome of supply-chain activities. The concept of mitigation is common in the risk-management literature, especially in the context of environmental disruption (Kleindorfer and Saad 2005, Tomlin 2006, Wagner and Bode 2008); and includes having appropriate insurance policies (Miller 1992). We assume risk mitigation has the same perspective as a coping with uncertainty strategy, and hence we categorise such approaches under this heading for the purposes of this review.

The main reason for dividing the literature into the two main categories is that it is first necessary to fully understand uncertainty before it can be addressed in practice; and so it is argued here that a full list of supply-chain uncertainty *sources* is a precursor to developing appropriate *management strategies*. By developing an understanding of the sources, 14 categories are identified in Section 3; many of these are themselves shown to be multi-dimensional, illustrating the complexity of the uncertainty phenomena in the supply chain. In addition, sources of uncertainty may be linked and so it is important to consider the impact (positive or negative) that managing one source of uncertainty may have upon another. Similarly, there may be more than one management approach for a particular uncertainty source. Therefore, a comprehensive list of management strategies is also needed before seeking to review how strategies and sources of uncertainty are aligned in the literature. By reviewing the literature, 10 reducing and 11 coping with strategies are identified.

Key authors for each of the types of supply-chain uncertainty model found in the literature are listed in Figure 2; and for uncertainty management approaches in Figure 3. The latter further lists some of the key management

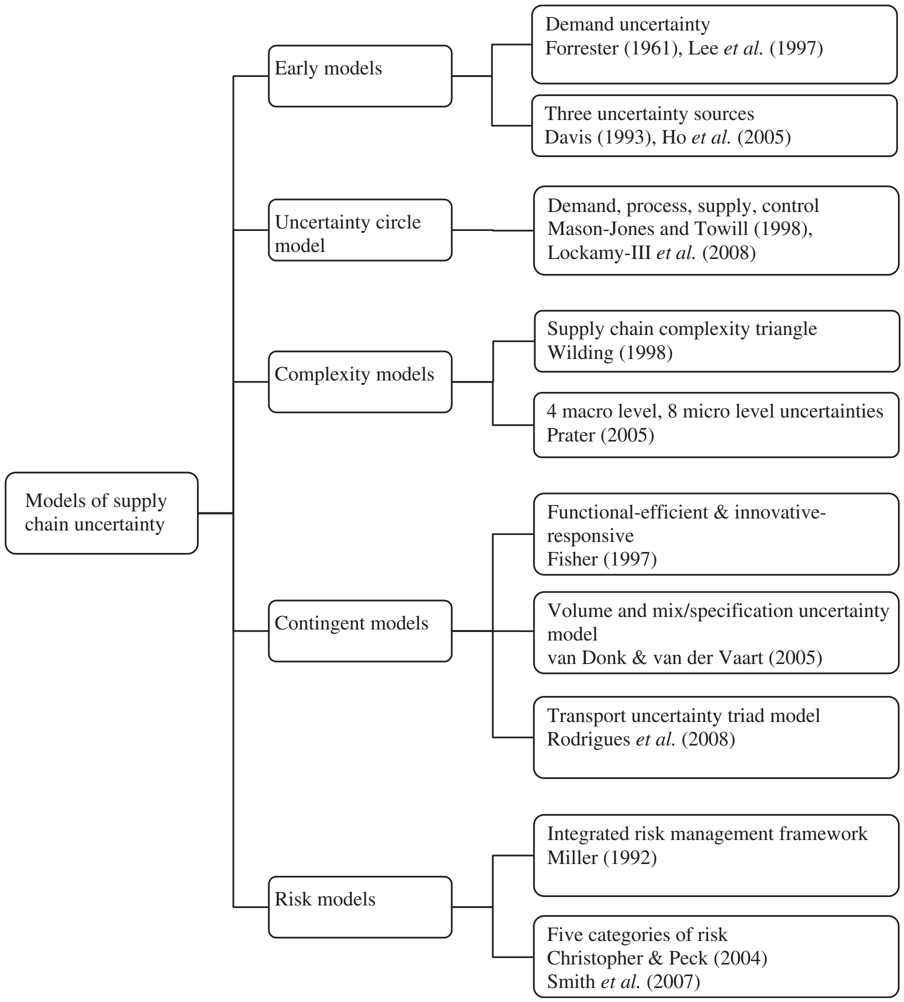

Figure 2. Models of supply-chain uncertainty: key references.

strategies including lean management; supply-chain integration; supply-chain flexibility and agility and risk mitigation. The following two sections discuss the material in each of the subcategories for sources of uncertainty and management strategies, respectively.

3. Identifying sources of uncertainty

Sources of uncertainty have been identified and presented in the literature through a number of models that have evolved over time, gradually becoming more complex. The discussion below begins with the simplest models that have been proposed in the literature, before moving on to more recent complex models. As each model is discussed, any additional sources of uncertainty included in that model will be highlighted. First, an early contribution was made by Davis (1993) who identified three sources of uncertainty: demand, manufacturing process, and supply uncertainty. This model suggests that demand and supply uncertainty have an effect on manufacturing process uncertainty, which in turn affects timely order fulfilment. Of these, the author suggested that demand uncertainty is commonly regarded as the most severe type, arising from volatile demand or inaccurate forecasts. This suggestion is supported by other authors, including van der Vaart *et al.* (1996) and Gupta and Maranas (2003). In this review, demand uncertainty is split into end-customer demand and demand amplification; thus four uncertainty sources are derived from this early literature.

The uncertainty circle model by Mason-Jones and Towill (1998) added a fifth source to those identified through the early work of Davis (1993): control uncertainty, which is concerned with the capability of an organisation to use

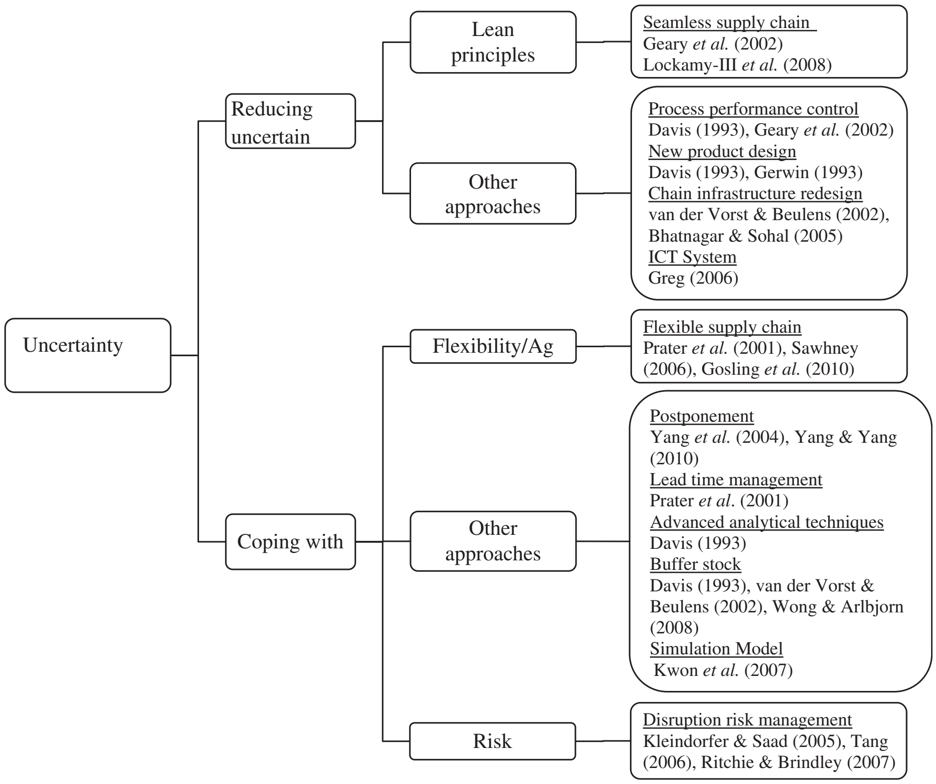

Figure 3. Uncertainty management: key references.

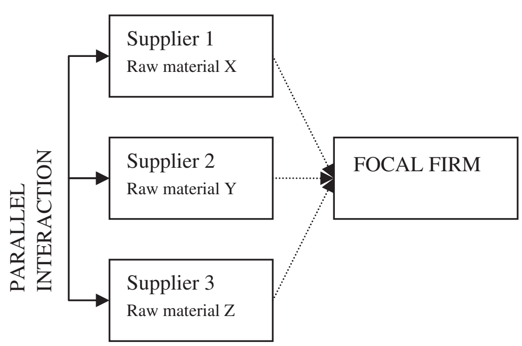

Figure 4. Parallel interaction.

information flow and decisions to transform customer orders into a production plan and raw material requirements (Geary *et al.* 2006). The supply-chain uncertainty circle contains four quadrants: demand side (without distinguishing between end customer demand and demand amplification); supply side; manufacturing process and control systems; and the model suggests that reducing these uncertainties will reduce cost. This is achieved through an integrated supply chain, which is believed to have minimal uncertainties in each of the four defined areas and hence is a means of combating uncertainty (Childerhouse and Towill 2002, Geary *et al.* 2002, Childerhouse and Towill 2004, Lockamy-III *et al.* 2008). The supply-chain uncertainty circle is arguably an explicitly clearer model than Davis' (1993) framework. First, it is more comprehensive, given that a fifth factor (control) is added. Second, subsequent work that uses this model suggests its theoretical importance in creating better performance and integration within the supply chain (e.g. van der Vorst and Beulens 2002, Yang and Burns 2003, Childerhouse and Towill 2004). This is due to the use of the model as a means of evaluating the level of supply-chain integration. Wilding (1998) proposed a 'supply-chain complexity triangle', which introduces a sixth important source of uncertainty which is labelled parallel interaction, as illustrated in Figure 4. This relates to complexity that arises due to the way in which a customer interacts with multiple potential suppliers. For example, when a first-tier supplier cannot supply its customer, the customer then has to coordinate and make order revisions with other first-tier suppliers. This disruption creates supplier uncertainty and reduces supply-chain performance. Wilding's (1998) complexity triangle has three key corners: amplification; deterministic chaos; and parallel interaction, as discussed above. Amplification is due to the bullwhip effect as identified by prior models, while deterministic chaos relates, for example, to control systems such as IS systems.

Wilding's (1998) model is a key example of a complexity model and has recently been enhanced by Prater (2005), who combined this with previous work (e.g. Davis 1993, Geary *et al.* 2002) to develop an important example of a micro/macro model. Prater (2005) not only highlighted four macro uncertainties but delved deeper to identify eight micro uncertainties. Macro-level uncertainty is a higher level category of uncertainty, whereas micro-level uncertainty relates to a more specific source of uncertainty which needs specific actions. For example, at the macro level is unforeseen uncertainty which then breaks down at the micro level into the bullwhip effect or parallel effects. Important new sources of uncertainty that arise from this model are grouped into a seventh source labelled decision complexity, which relates to the existence of multiple goals with uncertainty regarding the relative importance of each goal and to the existence of multiple constraints, some of which may be relaxed.

Other contributions can be classified as contingent models as they are made for specific purposes; for example, van der Vorst and Beulens (2002) studied uncertainty and supply-chain redesign in the food industry; Fisher (1997) developed a model to explain uncertainty in the fashion industry supply-chain supplying innovative products; and, van Donk and van der Vaart (2005) distinguished between two kinds of uncertainty: volume uncertainty and mix/specification uncertainty and used these two factors to develop four distinct situations of supply-chain uncertainty. These models identify further sources of uncertainty. In particular, van der Vorst and Beulens (2002) describe four further uncertainties caused by: chain configuration, infrastructure and facilities; order forecast horizon; Information Technology/Information Systems (IT/IS) complexity; and, human behaviour. In addition, all three of these papers identify a twelfth source of uncertainty that is linked to specific product characteristics.

Within the category of risk models, Miller (1992, 1993) developed an integrated risk management framework based on uncertainties faced by firms that operate internationally. The framework is based on the assumption that uncertainties can be explained by three factors: general environment, industry and firm. Werner *et al.* (1996) updated this framework after statistically testing the uncertainty factors. More recently, Juttner *et al.* (2003) and Christopher and Peck (2004) have differentiated risk sources into three categories: internal risk (process and control), network related (supply and demand), and external risk, and developed a framework to manage and mitigate risk.

The studies in the previous paragraph fail to acknowledge IT as a source of risk. Amit *et al.* (2005) argue that although IT solves some problems, paradoxically it can also increase supply-chain vulnerability in some cases due to increasing complexity and reliance on IT. Other studies, for example, by Bandyopadhyay *et al.* (1999), Finch (2004) and Smith *et al.* (2007) do discuss IT vulnerability. In addition, Savic (2008) also highlights the importance of IT (system and technology) risk, suggesting that it is one of five sources of operational risk: the other four sources discussed by Savic (2008) are organisation, processes and policies, people, and external events.

Most of the sources of risk in this literature are also discussed as sources of uncertainty in the models discussed above. The main contribution of these studies is to expand understanding of the associated sources of risk/uncertainty. Only two new sources are identified, adding to the twelve already mentioned above. Thus, the thirteenth source is environmental uncertainties (political, government policy, macroeconomic, and social); this paper also includes competitive uncertainties within this category. The fourteenth source is natural uncertainties which are related to natural disasters/accidents.

From the models described above, a total of 14 sources of uncertainty have been identified, as summarised in Table 1. These 14 sources can be divided into three groups:

(1) Uncertainties which come from the focal company, i.e. *internal organisation uncertainty* and include: product characteristics (U1), manufacturing process (U2), control/chaos (U3), decision complexity (U4), organisation/behavioural issues (U5) and IT/IS complexity (U6).
(2) *Internal supply-chain uncertainty* that arises within the realm of control of the focal company or its supply-chain partners, and comprises: end-customer demand (U7), demand amplification (U8), supplier (U9), parallel interaction (U10), order forecast horizon (U11), and chain configuration, infrastructure and facilities (U12).

Table 1. Sources of uncertainty.

	Factors/variables	Description and key literature
U1	Product characteristics	Product life cycle, packaging, perishability, mix, or specification Miller (1992), van der Vorst and Beulens (2002), Yang *et al*. (2004), van Donk and van der Vaart (2005)
U2	Process/manufacturing	Machine breakdowns, labour problems, process reliability, etc. Miller (1992), Davis (1993), Mason-Jones and Towill (1998), van der Vorst and Beulens (2002), Christopher and Peck (2004), Sheffi and Rice (2005), Sawhney (2006), Lockamy-III *et al*. (2008)
U3	Control/chaos/response uncertainty	Uncertainty as a result of control systems in the supply chain, e.g. inappropriate assumptions in an MRP system Mason-Jones and Towill (1998), Wilding (1998), Christopher and Peck (2004), Lockamy-III *et al*. (2008), Rodrigues *et al*. (2008)
U4	Decision complexity	Uncertainty that arises because of multiple dimensions in decision-making process, e.g. multiple goals, constraints, long term plan, etc. van der Vorst and Beulens (2002), Prater (2005), Xu and Beamon (2006)
U5	Organisation structure and human behaviour	E.g. organisation culture Miller (1992), van der Vorst and Beulens (2002), Sheffi and Rice (2005)
U6	IT/IS complexity	The realisation of threats to IT use in the application level, organisational level and inter-organisational level, e.g. computer viruses, technical failure, unauthorised physical access, misuse, etc. Bandyopadhyay *et al*. (1999), van der Vorst and Beulens (2002), Deane *et al*. (2009)
U7	End customer demand	Irregular purchases or irregular orders from final recipient of product or service Miller (1992), Davis (1993), Fisher (1997), Mason-Jones and Towill (1998), van der Vorst and Beulens (2002), Christopher and Peck (2004), Yang *et al*. (2004), Prater (2005), van Donk and van der Vaart (2005), Rodrigues *et al*. (2008), Lockamy-III *et al*. (2008)
U8	Demand amplification	Amplification of demand due to the bullwhip effect Davis (1993), Fisher (1997), Mason-Jones and Towill (1998), Wilding (1998), Yang *et al*. (2004), Prater (2005), van Donk and van der Vaart (2005), Lockamy-III *et al*. (2008)
U9	Supplier	Supplier performance issues, such as quality problems, late delivery, etc. Miller (1992), Davis (1993), Mason-Jones and Towill (1998), van der Vorst and Beulens (2002), Christopher and Peck (2004), Yang *et al*. (2004), Prater (2005), Sawhney (2006), Lockamy-III *et al*. (2008), Neiger *et al*. (2009)
U10	Parallel interaction	Parallel interaction refers to the situation where there is interaction between different channels of the supply chain in the same tier Wilding (1998), van der Vorst and Beulens (2002), Prater (2005)
U11	Order forecast horizon/ lead-time gap	The longer the horizon, the larger the forecast errors and hence there is greater uncertainty in the demand forecasts van der Vorst and Beulens (2002), van Donk and van der Vaart (2005)
U12	Chain configuration, infrastructure and facilities	E.g. number of parties involved, facilities used or location, etc. Miller (1992), van der Vorst and Beulens (2002)
U13	Environment	E.g. political, government policy, macroeconomic and social issues, competitor behaviour Miller (1992), Christopher and Peck (2004), Yang *et al*. (2004), Boyle *et al*. (2008), Rodrigues *et al*. (2008)
U14	Disruption/natural uncertainties	E.g. earthquake, tsunamis, non-deterministic chaos, etc. Miller (1992), Christopher and Peck (2004), Kleindorfer and Saad (2005), Prater (2005), Tang (2006), Tomlin (2006)

(3) *External uncertainties* from factors outside the supply chain, which are outside a company's direct areas of control, and include: environment (U13), for example, government regulation, competitor behaviour and macroeconomic issues, and disasters (U14), for example, earthquake, hurricane and high sea waves.

As discussed in Section 2 above, many of the sources of uncertainty are themselves multi-dimensional. These dimensions are discussed in detail in Appendix 1. For example, supply uncertainty (U9) can be due to the timing, quality or availability of products; while product characteristics (U1) can relate to uncertainty regarding a product's specification, packaging, perishability or the product life cycle and level of variety offered.

Table 2. Uncertainty factors and comparison of literature.

Factors/variables	Early model (Davis 1993)	Uncertainty circle model (Mason-Jones and Towill 1998)	Supply-chain complexity triangle model (Wilding 1998)	Micro/macro uncertainty model (Prater 2005)	Contingent model (van der Vorst and Beulens 2002)	Contingent model (van Donk and van der Vaart 2005)	Process maturity model (Lockamy-III *et al.* 2008)	Integrated risk model (Miller 1992)[a]	Risk sources model (Christopher and Peck 2004)[a]	IT vulnerability model (Smith *et al.* 2007)	Operational risk model (Savic 2008)[a]	New model
1 Product characteristic					X	X		X				X
2 Manufacturing process	X	X			X		X	X	X	X	X	X
3 Control/chaos uncertainty		X	X	X			X		X	X		X
4 Decision complexity				X	X							X
5 Organisation/ behavioural issues					X			X			X	X
6 IT/IS complexity					X					X	X	X
7 End-customer demand	X	X		X	X	X	X	X	X	X		X
8 Demand amplification		X	X	X	X	X	X					X
9 Supplier	X	X			X		X	X	X	X		X
10 Parallel interaction			X	X	X							X
11 Order forecast horizon					X							X
12 Chain infrastructure and facilities					X			X				X
13 Environment								X	X	X		X
14 Disaster								X	X	X	X	X

Note: [a]Risk-related literature.

3.1 *Research gaps: sources of uncertainty*

While the literature has identified all of these sources, we argue that additional work is needed to verify many of the sources of uncertainty using further empirical evidence, particularly where a factor is only identified in a small number of previous publications. Appendix 1 is comprehensive in indicating the extent of previous research and of the context in which any empirical evidence has been collected. There is also a need to confirm whether each factor is significant to the generation of uncertainty in general or in particular industrial contexts (Yang *et al.* 2004). In addition, as illustrated in Table 2 below, no single study has yet included all of the 14 sources; research that looks at the interplay between these sources and how they are likely to combine in practice in particular settings is also needed.

An example of a factor needing further research is IT which, as discussed above, is an emerging source which contributes to the generation of supply-chain uncertainty, especially, reliance upon the Internet. Rapid advancement in this area means the role of IT is becoming more important in every type of business and that, paradoxically, not only does IT solve some supply-chain problems, it also increases supply-chain vulnerability. Although there is a growing body of research to understand the impact of the Internet on different SCM activities, authors such as Giménez and Lourenço (2004), Amit *et al.* (2005), Smith *et al.* (2007), and Savic (2008) argue that current research activity lacks clarity and that there is more to learn about the effects of IT and the Internet on supply-chain management.

4. Identifying supply-chain uncertainty management strategies

Having identified a comprehensive list of the sources of uncertainty, this paper now seeks to identify a comprehensive list of management approaches. As discussed in Section 2, these approaches are classified into reducing uncertainty and coping with uncertainty strategies. Ten of the former are identified in the discussion in Section 4.1; while 11 of the latter are discussed in Section 4.2. Research gaps specific to the management strategies themselves are described in Section 4.3.

4.1 *Reducing uncertainty strategies*

First, Davis (1993) proposed three reducing uncertainty strategies: total quality control; new product design, and supply-chain redesign. The first two strategies can be used to reduce process uncertainty (Gerwin 1993, Geary *et al.* 2002); while the latter can reduce supply and demand related uncertainty. Elements of the supply chain to consider for redesign include: (1) chain configuration, e.g. structure, facilities, members involved; (2) chain control, i.e. decision functions that manage execution of operational activities and strategic objectives; (3) chain information systems; and (4) chain organisation and governance, i.e. responsibilities and authorities (van der Vorst and Beulens 2002; Bhatnagar and Sohal 2005).

In addition to the redesign of supply-chain configuration and/or infrastructure, van der Vorst and Beulens (2002) also suggested two other strategies for reducing uncertainty. First, collaboration with key suppliers and customers helps to break barriers between supply-chain stages; this may reduce uncertainty related to decision-making complexity within the system, as also suggested by Helms *et al.* (2000) and Charu and Sameer (2001). Second, human behaviour related uncertainty can be reduced by limiting the role of humans in the process. This could be achieved by utilising process automation or otherwise simplifying bureaucratic decision-making policies and procedures.

The concept of collaboration has been further studied by authors who suggest that the ‘seamless supply chain’, where every member of the chain is highly integrated and ‘acts as one’, will lead to reductions in process, supply, demand and control uncertainty (Childerhouse and Towill 2002, Geary *et al.* 2002, Childerhouse and Towill 2004). Here, an integration strategy means extending the management systems upstream to suppliers and downstream to customers, having first achieved functional and internal integration. For example, Geary *et al.* (2002) discussed the ‘well-trodden path’ as a systematic way towards a seamless supply chain in which control uncertainty is reduced first in conjunction with process uncertainty, then in conjunction with supply, and finally, with demand uncertainty. This requires the elimination of waste through lean strategies and the synchronisation of material flows throughout the supply chain. A recent study of US and European firms by Lockamy-III *et al.* (2008) supports the viability of seamless supply chains. However, their research is universalistic rather than addressing specific industry contexts; whereas lean (or efficient) approaches are generally associated with the production of standard products rather than the customised products associated with the agile supply chain and therefore not appropriate to all contexts.

Whether a lean or agile supply chain is appropriate, effective information sharing is usually an essential part of a collaboration strategy, and firms will often rely on the application of Information and Communication Technology (ICT) for this purpose (Gunasekaran and Ngai 2004). These ICT solutions may then provide the basis for an appropriate Decision Support System (DSS), which in turn may reduce control uncertainty by enhancing the process and quality of decision-making (Mason-Jones and Towill 1998, Mason-Jones and Towill 2000, Childerhouse and Towill 2004). However, mismanagement of the information-sharing process, involving for instance, inaccurate data, may cause difficulties in making good decisions; hence, control uncertainty may increase. To reduce uncertainty related to ICT complexity, Deane *et al.* (2009) discussed various approaches, such as periodic employee training and awareness, periodic testing and review procedures, monitoring/logging procedures, backup and recovery procedures, and protection for all sensitive informational assets.

Another approach to reducing demand uncertainty is pricing strategy/promotion incentives (Lee *et al.* 1997, Gupta and Maranas 2003). Well-established research in this area suggests that revising prices or using controlled marketing promotions are effective ways of reducing the bullwhip effect.

Finally, Fisher (1997) proposed responsive stock replenishment, where the period of planning is shorter than the forecast horizon, to reduce uncertainty related to innovative products which are characterised by a short product lifecycle and a wide variety of products. An empirical study in the food industry revealed that by applying a shorter stock replenishment cycle (less than one month) than the minimum product life cycle (6 months), the case company was able to satisfy demand and had sufficient time to sell off excess stocks in the case of end-of-product-life items.

In summary, the strategies discussed above from the literature for reducing uncertainty can be categorised into 10 types (R1–R10) as further defined in Table 3. These strategies are lean operations, product design, process

Table 3. Uncertainty-management strategies.

	Description
Reducing strategy (R)	
R1. Lean operations	By making a process leaner, it becomes a simpler process with less inherent uncertainty (Hines *et al*. 2004, Taylor 2006, Tracy and Knight 2008)
R2. Product design	Establishing a good initial design or changing the design of a product to enable a better and more robust manufacturing process (Davis 1993)
R3. Process performance measurement	Using process performance measures, e.g. quality measures, machine performance indicators, and key performance indicators (KPIs), to detect and hence reduce uncertainty (Geary *et al*. 2002)
R4. Good decision support system (DSS)	Refers to the use of decision-support systems as a problem-solving strategy for complex decision-making situations (Muckstadt *et al*. 2001, Shim *et al*. 2002)
R5. Collaboration	Proactive initiatives, where people play a dominant role, to reduce uncertainty within the scope of the activities described below: • Internal integration that provides synchronised decision and control functions in the organisation (van der Vorst and Beulens 2002) • Vertical integration as a way to control supply or demand uncertainties (Miller 1992) • Contractual agreements with suppliers or buyers to reduce uncertainty (Miller 1992) • Voluntary restraint of competition by alliances, joint ventures, franchising agreements, technology licensing agreements, and participation in consortia (Miller 1992) • Partnership programmes by working more closely with suppliers or customers, for example, in terms of collaborative planning, forecasting and replenishment (CPFR) initiatives (Muckstadt *et al*. 2001, Christopher and Peck 2004, Holweg *et al*. 2005), to reduce uncertainty regarding problems of other members of the supply chain. • E-intermediation to facilitate greater information sharing so that adequate information is available for key tasks (Boyle *et al*. 2008)
R6. Shorter planning period	Runs a planning system in a shorter period than the forecast horizon, thereby reducing the number of last minute changes to the schedule. For example, a manufacturer may carry out weekly production plans and product replenishment to retail outlets whereas retailers send monthly forecasts (Fisher 1997).
R7. Decision policy and procedures	Refers to the use of better decision policy and procedures to improve supply-chain processes. For example, bureaucratic decision-making policies require signatures from several people, making it a difficult and lengthy procedure. Therefore, redesigning procedures to reduce the number of signatures will reduce inherent uncertainty (van der Vorst *et al*. 1998, van der Vorst and Beulens 2002).
R8. ICT System	A strategy to use application software, computer hardware and communication technology. For example, the use of specific software, e.g. virus-removing software and firewall software, to prevent damage to the IT/IS system caused by software-based attacks (Bandyopadhyay *et al*. 1999, Greg 2006).
R9. Pricing Strategy	Refers to the use of a pricing strategy or other incentives to reduce demand uncertainty. Marketing activities such as price promotions could influence end-consumer demand to favour an organisation's plan and hence help with managing uncertainty caused by seasonal demand variability (Miller 1992, Gupta and Maranas 2003).
R10. Redesign of chain configuration and/or infrastructure	Refers to the process of redesigning the supply-chain configuration and/or infrastructure, i.e. the plants, distribution centres, transportation modes, production processes and network relationships, which will be used to satisfy customer demands. The redesign of supply chains often lead to big impacts that span large parts of the organisation, and not just incremental changes (Harrison 2001). For example: • How many plants are needed? What process technologies should be employed (Harrison 2001)? Or, how close should each plant be to key customers (Davis 1993)? • Supply base design and selection of suppliers (Harrison 2001) • Outsourcing, e.g. using a third-party logistics company (Lee 2002, Sun *et al*. 2009) • Infrastructure for new products or processes (Harrison 2001) • Chain configuration, governance structures, etc. (van der Vorst and Beulens 2002).
Coping with uncertainty strategy (C)	
C1. Postponement	Delaying activities or processes until the latest possible point in time makes it possible to make things according to known demand rather than to forecast demand (Yang *et al*. 2004, Yang and Yang 2010). Toyota, for example, delays decisions on critical specifications until the last possible moment when market information is more definite (Yang *et al*. 2004).

(*continued*)

Table 3. Continued.

	Description
C2. Volume/delivery flexibility	The agility to manufacture a product despite changes to volume and mix (Braunscheidel and Suresh 2009). This can be achieved by providing dedicated production facilities or multiple production facilities (van Donk and van der Vaart 2005), or by using multi–skilled workers (Miller 1992).
C3. Process flexibility	The flexibility of the workforce, plant and equipment enable a company to cope with uncertainty caused by frequent product changeovers on the shop floor. For example, multi-skilled workers may lead to process flexibility (Miller 1992). In addition, process flexibility could be achieved through the implementation of general purpose machines, equipment and technologies (Miller 1992, Ulrich 1995).
C4. Customer flexibility	Exploiting relationships with customers that are less sensitive to uncertainty issues and are able to adapt their plans. For example, uncertainty caused by unexpected machine breakdowns in the Printed Circuit Board (PCB) industry may be passed to flexible customers who are less sensitive to the problem (Sawhney 2006).
C5. Multiple suppliers	Exploiting the availability of potential suppliers and their willingness to help an organisation manage its sources of uncertainty. For example, multiple suppliers may enable an organisation to cope with changing production plans caused by production problems by choosing a supplier that provides prompt delivery of raw materials (Sawhney 2006).
C6. Strategic stocks	Refers to the use of inventory to buffer against uncertainty (Davis 1993, Helms *et al.* 2000, Wong and Arlbjorn 2008).
C7. Collaboration	Basic/limited information sharing internally within an organisation or with chain partners (suppliers and customers) but, in contrast to the reducing strategy of R5, this is without affecting the source of uncertainty. For example, a manufacturer may have exchange of information with customers, e.g. retailers, that helps to increase forecast accuracy of end-customer demand; these coordination activities, however, do not affect end-customer demand patterns (Muckstadt *et al.* 2001).
C8. ICT system	The availability of a computer based information system to provide information transparency between supply-chain partners, which then enables better and faster information flow, but in contrast to R8, this is without reducing the source of uncertainty. For example, an ICT system may facilitate information sharing for managing end-customer demand variations, in terms of cost efficiency and responsiveness to end-customer orders (Mason-Jones and Towill 1998, Towill and McCullen 1999, Prater 2005).
C9. Lead-time management	Refers to the quoting of a longer lead time for customer orders compared with the expected manufacturing lead time (Prater *et al.* 2001).
C10. Financial-risk management	Refers to techniques of financial risk-mitigation such as purchasing insurance, e.g. business interruption insurance, and buying and selling financial instruments, e.g. forward and futures contracts (Tomlin 2006, Ritchie and Brindley 2007).
C11. Quantitative techniques	Employing operations research techniques, e.g. forecasting, simulation, and mathematical modelling, to reduce the impact caused by a source of uncertainty (Peidro 2009).

performance measurement, DSS, collaboration, a shorter planning period, decision policy and procedures, ICT system, pricing strategy, and redesign of chain configuration and/or infrastructure.

4.2 *Coping with uncertainty strategies*

Supply chain flexibility has been suggested as an approach for coping with sources of uncertainty (Prater *et al.* 2001, Sawhney 2006, Gosling *et al.* 2010). For example, Sawhney (2006) developed a transformation framework of flexibility by adapting transformation system theory (inputs, processes, and outputs). At the input stage, an organisation creates input flexibility by employing multiple suppliers (Sawhney 2006). However, adding more suppliers may increase supply risk, such as quality issues or delivery reliability, especially for sourcing critical items and the cost is also higher for managing multiple suppliers (Lee 2002). Therefore, a careful balance is needed. At the process stage, labour flexibility and machine flexibility can be used to manage equipment, people, and infrastructure uncertainty (Sawhney 2006). At the output stage, customer flexibility is used when customers are less sensitive to delivery dates or products (Prater *et al.* 2001, Pujawan 2004).

Further strategies to cope with demand uncertainty include: postponement (Lee and Billington 1995, Yang *et al.* 2004, Yang and Yang 2010); information sharing between a manufacturer and its downstream partners, such as retailers (Lee *et al.* 1997); support from ICT systems (Towill and McCullen 1999, Prater 2005); use of strategic buffer stocks (Davis 1993, Helms *et al.* 2000, Wong and Arlbjorn 2008); and lead-time management (Prater *et al.* 2001). The latter entails making delivery lead time promises to retailers that are longer than the actual lead time, providing the manufacturer with the flexibility to cope with unexpected changes in orders caused by end-customer demand uncertainty. This has the obvious disadvantage of reducing speed to market and so is only appropriate in contexts in which speed is not a competitive priority.

Drawing on the risk management literature, financial measures such as insurance is one of the most common strategies for mitigating risk, and hence lessens the severity of disruptions, such as natural disasters, on supply-chain activities (Kleindorfer and Saad 2005, Tang 2006, Ritchie and Brindley 2007).

Finally, it is noted that a great deal of research can be found related to coping with uncertainty using advanced quantitative techniques; the recent study by Peidro *et al.* (2009) reviews and classifies quantitative techniques for supply-chain planning under uncertainty. The detail behind the quantitative models subcategory of our review is beyond the scope of this paper; however, the reader may refer to the following for examples of relevant research in this area (Koh and Saad 2002, Gupta and Maranas 2003, Kwon *et al.* 2007) and to the recent literature review mentioned above (Peidro *et al.* 2009).

In summary, the literature suggests 11 strategies for coping with uncertainty, as summarised in Table 3, and labelled C1-C11 in the remainder of the paper. These strategies are: postponement, volume/delivery flexibility, process flexibility, customer flexibility, multiple suppliers, strategic stocks, collaboration, ICT system, lead-time management, financial risk management, and quantitative techniques. It is noted that collaboration is also included as a reducing uncertainty strategy, given that it can be used both to reduce uncertainty by sharing better supply-chain information and to cope with uncertainty when it arises unexpectedly. Similarly, ICT appears in both categories. Thus, in total, 21 management strategies for coping with/reducing uncertainty have been identified in the literature.

4.3 *Research gaps: uncertainty management*

One of the key areas for further research is to develop more contingency-based research in the management of supply-chain uncertainty. For example, as discussed above, previous research into supply-chain integration to create a seamless supply chain is unlikely to be applicable in all contexts given its reliance on lean, making it less flexible in the face of disruptions (Hines *et al.* 2004). The study by Geary *et al.* (2002) only uses automotives and its related industry as an example, and while the later study by Lockamy-III *et al.* (2008) is a survey of a large number of firms, it does not attempt to identify specific contexts in which this approach will apply, but rather adopts a universalistic standpoint. In addition, with the increasing number of global supply-chain members, the challenge to coordinate becomes more critical, especially when product life cycles are short.

A second area of research is the viability of management strategies, particularly where their implementation incurs costs. For example, although Stevenson and Spring (2007) suggest that flexible capabilities may lead to a competitive advantage when a firm's competitors are unable to deal with uncertainty, other authors note that such flexibility is costly (Gunasekaran and Ngai 2004). Therefore, further research is needed to analyse 'optimal' flexible solutions which do not unduly sacrifice cost-effectiveness.

Further areas of research include the need to consider the impact of each management strategy on sources of uncertainty, and to verify this through empirical research. To discuss this further, it is first necessary to build a theoretical foundation for future research, as described in the following section.

5. Building a theoretical foundation for future research

As a lens through which to study supply-chain uncertainty, this section builds a theoretical model by drawing on manufacturing strategy theory, which is itself based on contingency and alignment theory, as explained below. Thus, the rationale for the theoretical model is first justified, before being outlined and then populated using the material from the literature reviewed above.

Manufacturing strategy theory acknowledges that manufacturing strategy is influenced by environmental uncertainty and is a major determinant of business performance (Swamidass and Newell 1987). The rationale underlying this theory is that there is a causal relationship between a firm's external environment and its strategic profile; and that, in turn, the manufacturing strategy, selected from strategic choices, has a major effect on performance (Swamidass and Newell 1987, Ho *et al.* 2005). The theory of manufacturing strategy has been used in previous supply-chain research; for example, Ward *et al.* (1995) used the theory to empirically investigate the effects of the environment on performance in manufacturers in Singapore; Tracey *et al.* (2005) used the constructs of the theory to test supply-chain capabilities; and Sawhney (2006) adapted the theory to develop a transformation model of supply chains by using variables of flexibility and uncertainty. It is therefore argued to be of relevance to the general area of supply-chain management.

The theory of manufacturing strategy has been argued to be linked to contingency theory (Ward *et al.* 1995, Ho 1996); and hence can also be described as a contingency model. Contingency theory proposes that the most appropriate approach to management strategy in a particular context is dependent upon a set of 'contingency' factors – which may include uncertainty of the environment, i.e. the relevant sources of uncertainty (Downey and Slocum 1975, Tosi Jr and Slocum Jr 1984, Ho 1996, Wagner and Bode 2008). A further concept which is relevant to the theory of manufacturing strategy is that of 'alignment', although this is not explicitly referred to by Swamidass and Newell (1987). In the context of alignment theory, Drazin and van de Ven (1985) argue that fit or alignment is the key issue in a contingency theory based model; an organisation should develop a strategy which aligns its strategic choices with environmental requirements, as also discussed in the studies by Mintzberg (1978), Ho (1996), and Wagner and Bode (2008). If this alignment is in place, then it will lead to improved business performance. In the context of supply-chain uncertainty, it can be argued that the performance of an organisation is strongly related to the 'alignment' between: (1) sources of uncertainty and managerial perceptions of them (Lawrence and Lorsch 1967); and (2) the choice of uncertainty management strategy (Ward *et al.* 1995, Christopher 2006). Thus, alignment theory can be argued to apply, as confirmed by the research of Lee (2002) and Sun *et al.* (2009), in which alignment between the levels of demand and supply uncertainty and archetypal management strategies – efficient, responsive, risk-hedging and agile – are shown to have a positive impact on perceived performance.

Given the applicability of the underlying contingency and alignment theories, it is argued that manufacturing strategy theory can be adapted to provide a strong theory to underpin future research in supply-chain uncertainty which incorporates a broader set of uncertainty sources than those considered in Sun *et al.* (2009), as shown in Figure 5. Beginning with the left-hand side of the figure, the term 'environmental uncertainty' from the manufacturing strategy theory is first enhanced to indicate that this will refer to all sources of uncertainty. It is important to clarify that such sources may be external to the supply chain or internal to it, as identified in Section 3 above. Thus, the term 'environment' is used broadly in Figure 5 to include any factors in a particular context that affect the choice of management strategy in the middle box. Second, this literature review in Section 4 above has identified the relevant content variables that are needed to operationalise the concept of supply-chain uncertainty management strategies. However, the process by which strategic decisions are made in an organisational setting (the process variable) is beyond the scope of this review, but nonetheless included in Figure 5 for completeness. To pursue research in this topic, the reader is referred to Neiger *et al.* (2009) and Hult *et al.* (2010) for recent papers looking at the process of identifying supply-chain risks and of assessing risks in practice, respectively.

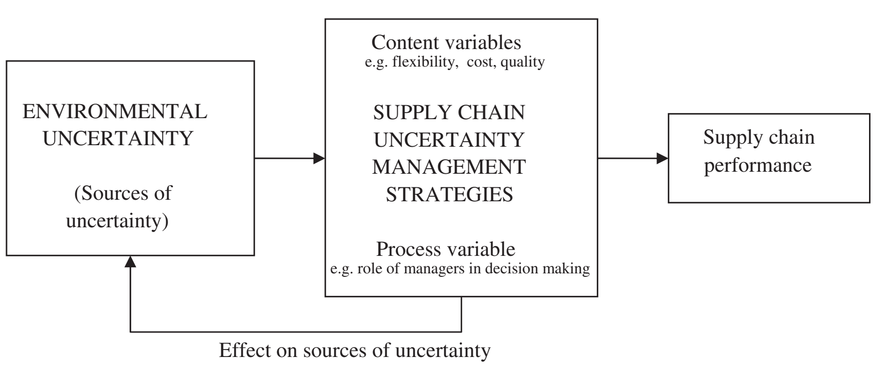

Figure 5. Contingency-theory-based model of supply chain uncertainty.

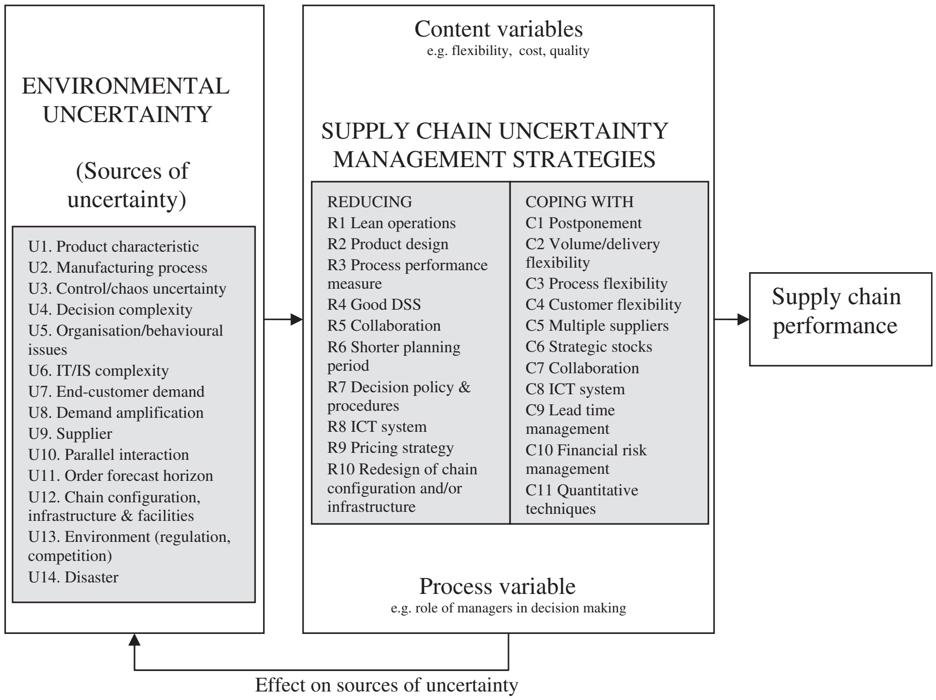

Figure 6. Populated model of supply-chain uncertainty.

Figure 5 also includes a feedback loop between uncertainty management strategies and sources of uncertainty. This feedback loop acknowledges that attempts to manage a source of uncertainty can sometimes have an impact on that source of uncertainty itself either positively or negatively; or on another source of uncertainty. For example, a strategy to implement an ERP system may improve production planning and reduce control uncertainty; on the other hand, a high dependency on such a computer-based system may initiate another uncertainty, for example in terms of delayed processes caused by computer/hardware problems.

The theoretical model in Figure 5 can be populated using the identified 14 sources of uncertainty and the 21 management strategies from the literature review, as shown in Figure 6 below. However, before discussing which of the uncertainty management strategies identified in Section 4 has been aligned with each specific source of uncertainty in the literature, thereby populating the theoretical framework, it is first necessary to consider the literature on measuring the impact of management strategies on performance. Melnyk *et al*. (2004) suggest that to maintain consistency of alignment and coordination, a performance measurement system is required. Performance measurement is also an important process to assess the viability of a strategy to improve performance (Gunasekaran *et al*. 2001). Previous studies have discussed ways to understand and measure the effectiveness of supply-chain strategies (e.g. Beamon 1999, Neely 1999, Gunasekaran *et al*. 2001, Chan 2003, Kleijnen and Smits 2003, Melnyk *et al*. 2004). These studies, however, have different approaches to performance measures. For example, Beamon (1999) classifies measures in three categories – output, resource, and flexibility; Gunasekaran *et al*. (2001) categorise measures on strategic, tactical, and operational levels; Kleijnen and Smits (2003) suggest employing a balanced scorecard; and Melnyk *et al*. (2004) propose four distinct measures – financial/outcome, financial/predictive, operational/outcome, and operational/predictive. Despite these different perspectives, performance measures can be broadly categorised as financial measures (e.g. raw material cost, sales revenue, manufacturing cost, inventory cost, and transportation cost) and non-financial measures (e.g. cycle time, customer service level, inventory levels, resource utilisation, and quality).

In terms of supply-chain uncertainty research, previous studies have tended to only provide general explanations about the impacts of uncertainty management strategies on performance. For example, Mason-Jones and Towill (1998) and Geary *et al*. (2002) explain that reducing four sources of uncertainty (*demand*, *process*, *supply* and *control*) will improve *financial* performance (e.g. in terms of cost reduction). Here, a specific performance measure – *cost* – is affected by the collective management of several sources of uncertainty at once. Other studies, e.g. Davis (1993), Yang *et al*. (2004), and Prater (2005), propose an uncertainty management strategy to improve supply-chain

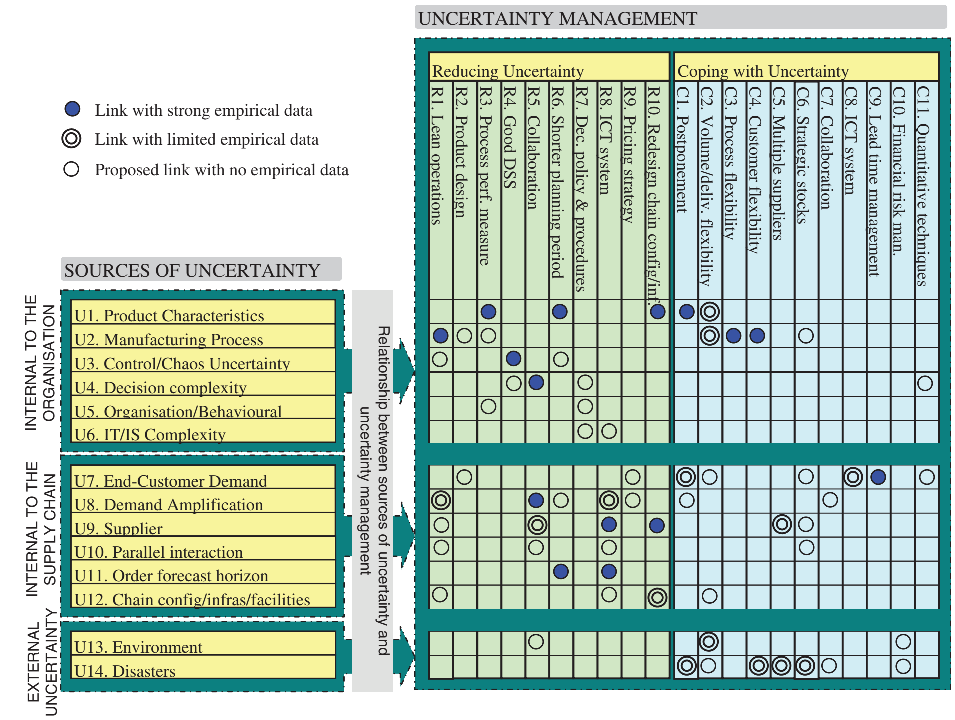

Figure 7. Alignment between sources of uncertainty- and uncertainty-management strategies.

performance, but without explicit explanation of any performance measures. The lack of explanation on specific performance measures makes it difficult to use previous studies to determine the actual expected changes in performance. In practice, it is of course often difficult to determine the effect of a particular strategy on any performance measure, as there are so many factors at play. Nonetheless, a greater understanding of the effects of strategies on the competitive position of an organisation is essential for managers in the field. Thus, although the theoretical model assumes appropriate alignment will improve performance, further research is needed to determine the effect of many of the supply-chain management strategies listed in Figure 6.

For each dimension of each source of uncertainty, Appendix 2 tabulates the management strategies with which it has been linked in the literature. In these tables, the effect of these strategies on performance is only indicated when previous studies provide specific information. Appendix 2 also shows that empirical evidence is provided in a minority of areas, with secondary data or conceptual research being more common grounds for proposing the alignment. This detailed analysis is summarised in Figure 7, where a distinction is made between: (1) uncertainty/management strategy links supported by empirical evidence for at least one dimension of the source (referred to as 'strong empirical evidence'); (2) links where there is only secondary empirical evidence for at least one dimension of the source of uncertainty (referred to as 'limited empirical evidence'); and (3) links with no empirical evidence.

There are some patterns in Figure 7 worthy of comment. First, for sources of uncertainty that are due to the internal organisation, the methods of managing uncertainty tend to be concentrated under the reducing category. In contrast, reducing and coping strategies have a similarly important role to managing uncertainty internally, while, for sources of uncertainty that are external to the organisation, all of the strategies are in the coping category. This would suggest that reducing uncertainty is always preferable where feasible, as the long term benefits outweigh the costs which may only be apparent in the short term, although empirical research is needed to confirm this. Second, approaches including lean, collaboration and flexibility are most able to address several of the sources of uncertainty. This supports the current emphasis on flexibility/agility and lean as key approaches in the literature; and, confirms that more research is needed into the complex issue of collaboration, including the quality of the relationship between collaborators which may involve trust, confidence and/or power (Burgess *et al.* 2006). In general, the figure highlights the lack of strong empirical evidence for most links between uncertainty sources and management strategies. Most of the strong empirical evidence is for the most well-known sources of uncertainties, such as product, manufacturing process and supplier uncertainty. In contrast, there is no empirical evidence on how to manage parallel interaction, and there is no strong empirical evidence that links uncertainties that are external to the supply chain to management strategies.

As shown in Appendix 2, several strategies have been proposed for many of the specific dimensions of sources of uncertainty, thus suggesting that both reducing and coping with strategies can be applied independently or together for each source of uncertainty. It can also be argued that some strategies can be used to either reduce or cope with uncertainty when dealing with different types of uncertainty. For example, real-time ICT may *reduce* the effect of demand amplification (U8) and may help to *cope with* fluctuations in end-customer demand (U7). The former results from technology solutions that enable direct access to end-customer sales information, which in turn enhances the accuracy of manufacturing production planning (van der Vorst and Beulens 2002). However, this flow of information does not influence end-customer demand fluctuations in itself, so for this source of uncertainty, real-time ICT helps the manufacturer to minimise the impact.

It is noted that while the links between sources of uncertainty and management strategies draw heavily on literature evidence, the model is nonetheless considered to require further clarification with empirical evidence to both verify the links and develop a better understanding of them. As discussed, for the link between a management strategy and its impact on performance, there is very little evidence in the literature and so here, rigorous empirical study is needed to populate the theory further, perhaps removing some links where the impact on performance is negligible. For example, the literature has suggested that uncertainty regarding end-customer demand can be reduced using pricing strategies or can be coped with using: postponement, strategic stocks, real-time ICT, lead-time management, or quantitative models. However, it is not yet clear which of these approaches is widely used in practice, which is most effective in terms of performance or whether there are circumstances in which one may be preferred over another. There is also a question regarding whether there is any interplay between the various uncertainty management approaches, i.e. whether solving one source of uncertainty can influence (positively or negatively) other sources of uncertainty. Finally, the proposed theoretical model makes no distinction between different degrees of uncertainty for each source; whereas the degree could vary in practice from being of low concern within an organisation to being of very high concern. Understanding the degree of uncertainty and hence concern for each source may be important in prioritising management actions. However, as most of the current literature does not address the degree, there is as yet insufficient evidence to include this in the theoretical model. A notable exception is the research by Sun *et al.* (2009), which considers high and low levels of demand and supply uncertainty, showing that alignment will vary according to the level. Extending their research into other sources of uncertainty is also a rich area for future research.

Finally, the development of the theoretical framework described above has been driven by the use of contingency and alignment theory, providing a high level theory for future research. However, it is acknowledged that several other candidate theories exist for the study of specific links between sources of uncertainty and their management strategies. For example, agency theory in particular offers a potentially important interpretive frame for future empirical research. Agency theory attempts to explain the relationship between one party (the principal) and another (the agent), to which work is delegated (e.g. Jensen and Meckling 1976, Eisenhardt 1988, 1989). Delegating work involves an element of uncertainty and presents clear potential for moral hazard or opportunistic behaviour on the part of the agent (Eisenhardt 1989, Rossetti and Choi 2008). More specifically, moral hazard is likely to occur when the agent has an incentive to gain financially at the principal's expense. For example, there are clear opportunities for moral hazard when multiple suppliers interact or collude with one another, i.e. parallel interaction. Suppliers of the same material may, for example, collude in order to withhold stocks and increase the price that buyers are prepared to pay. The suggestion in this literature is that moral hazard can be overcome if the principal can increase goal congruence with the agent, such as through contracts and incentives; collaboration may also be an important practice, as suggested in Figure 7.

6. Conclusion

Using existing models of supply-chain uncertainty, and other related literature on uncertainty and risk, this review has developed a theoretical foundation for future research in this area. The resulting theoretical model provides a framework for further analysis and practical application. It has sought to be comprehensive in determining a full set of sources of uncertainty, and 14 key areas have been identified, as described in Table 1; and a full set of uncertainty management strategies, grouped into 10 strategies for reducing uncertainty and 11 strategies for coping with uncertainty, as described in Table 3. Many of the sources of uncertainty have been shown to be multi-dimensional, and the appendices provide a full set of these dimensions along with the associated literature and management strategies. Appendix 2 also indicates the expected improvements in performance when strategies are appropriately aligned with sources of uncertainty when literature evidence has specified the expected changes in key performance metrics.

The review concludes that there are many sources of uncertainty and management strategies that still require future research in their own right. These include the effects of parallel interaction, decision complexity and IT complexity. However, more importantly, there have been no previous studies that have sought to take a comprehensive view of supply-chain uncertainty and to look at the interplay between the various sources of uncertainty and management strategies. Moreover, there has been insufficient empirical research in this area to validate the proposed theories and establish the effects of strategies on performance. Therefore, there is also a research gap to carry out empirical case study or action research to simultaneously consider all of the sources of uncertainty in the model shown in Figure 7 in order to determine which are key in a particular context, and how these should be managed. Such research should pay particular attention to the effects of attempts to manage uncertainty both on the sources of uncertainty themselves, and on other key performance measures. There is scope for such research in all sectors of the manufacturing industry, as well as service supply chains. However, contexts with inherent uncertainty and global supply networks, such as the food industry, may provide the richest context for such research; and, may also generate new sources of uncertainty and management strategies.

In terms of managerial implications, this review addresses a complex issue which many managers seek to address. Figure 7 provides such managers with a starting point for first developing a better understanding of the uncertainty phenomenon in their organisation; and, second for considering alternative ways to manage specific aspects of it. Further research is needed to assess the process by which this theory can be embedded into the managerial decision-making processes of an organisation. In particular, in carrying out the empirical research suggested above, it will be important to look at how to prioritise the uncertainties to be addressed in a given industrial setting and which management actions are most effective in reducing more than one key source of uncertainty at once.

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Appendix

Appendix 1. Profile of the sources of uncertainty.

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
U1. Product characteristics	The product specification, e.g. colour, length, size, and packaging, can lead to uncertainty in processing times, e.g. when a product is new and the specification is not yet fully clarified	van Donk and van der Vaart (2005)	NA
	The packaging characteristics, e.g. uncertainty about how a new product is to be packaged can lead to uncertainty in product handling times	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food
	The product life cycle, e.g. shorter life cycles lead to uncertain output volumes, as there are more frequent new product introductions, leading to more frequent quality and engineering problems	Miller (1992), Fisher (1997), Sawhney (2006)	Sawhney (2006): Electronics
	The perishability of products leads to uncertainty in output volumes, etc.	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food
	The product variety offered: this leads to uncertainties in the quantities of product to stock, etc.	Fisher (1997)	NA
U2. Manufacturing process	Machine breakdowns lead to uncertain output volumes	Miller (1992), Davis (1993), Koh *et al.* (2002), Towill *et al.* (2002), Sawhney (2006)	Towill *et al.* (2002): Automotive Sawhney (2006): Electronic
	Variable process yield and scrap-rates lead to uncertain output volumes	Miller (1992), van der Vorst *et al.* (1998), Towill *et al.* (2002), van der Vorst and Beulens (2002)	Towill *et al.* (2002): Automotive van der Vorst and Beulens (2002): Food
	Changes in employee productivity due, for example, to labour absence, turnover, labour unrest or strikes	Miller (1992), Sawhney (2006)	Sawhney (2006): Electronics
	Accidents, that disturb the production process	Miller (1992)	NA
	General: authors who do not specify a dimension	Mason-Jones and Towill (1998), Geary *et al.* (2002), Christopher and Peck (2004)	NA
U3. Control/chaos uncertainty	Difficulties in production planning when the sales order is small compared with the production-batching system	Wilding (1998), Geary *et al.* (2002), Towill *et al.* (2002)	Towill *et al.* (2002): Automotive
	Chaos resulting from supply-chain control systems, e.g. wrong control rules, mismatch in the ICT system	Geary *et al.* (2002), Towill *et al.* (2002), van der Vorst and Beulens (2002), Prater (2005)	Towill *et al.* (2002): Automotive, van der Vorst and Beulens (2002): Food (limited evidence)
	Errors caused by inaccuracies or poor reports from supply-chain partners which are beyond the control of the organisation	Geary *et al.* (2002)	NA
U4. Decision complexity	Different goals across functional departments, which may or may not be mutually supportive, that disrupt supply-chain processes, e.g. in terms	Prater (2005)	NA

(*continued*)

Appendix 1. Continued.

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
	of delayed decisions that slow down the whole process		
U4. Decision complexity (contd)	Capacity constraints, e.g. maximum production output, machine utilisation, warehouse and truckload capacity including availability of rental options, etc., that leads to the uncertainty of the delivery of an order to the customer	Prater (2005)	NA
	Uncertainty inherent in long range traditional strategic planning, e.g. technology innovations or price/cost changes	Prater (2005)	NA
	Administrative issues and decision policies that lead to uncertainty in the supply-chain caused by unresponsive decision processes	van der Vorst *et al.* (1998)	van der Vorst *et al.* (1998): Food (limited evidence)
U5. Organisation/ behavioural	General behavioural issue, e.g. risk taker vs. risk averse behaviour, that leads to disruption in supply-chain processes	van der Vorst *et al.* (1998), Wilding (1998)	van der Vorst *et al.* (1998): Food (limited evidence)
	Political influence in an organisation that leads to the uncertainty of the execution of a supply-chain decision, e.g. senior versus junior employees/ managers	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food (limited evidence)
U6. IT/IS complexity	IT/IS system unavailability that may stop all supply-chain activities	Bandyopadhyay *et al.* (1999), Finch (2004), Smith *et al.* (2007), and Savic (2008)	NA
	Data/information security issues that lead to uncertainty, e.g. in terms of information integrity and trust in the system	Bandyopadhyay *et al.* (1999), Finch (2004), Smith *et al.* (2007), and Savic (2008)	NA
	IT/IS system performance that leads to uncertainty, e.g. in terms of productivity of processes	Bandyopadhyay *et al.* (1999), Finch (2004), van der Vorst and Beulens (2002), Prater (2005), Smith *et al.* (2007), and Savic (2008)	van der Vorst and Beulens (2002) Food (limited evidence)
U7. End-customer demand	Seasonal demand variability, e.g. Christmas, Eid al-Fitr, Chinese New Year, school holidays, dry or rainy seasons.	Lee (2002), van der Vorst and Beulens (2002), Sun *et al.* (2009)	Lee (2002): fashion (limited evidence) van der Vorst and Beulens (2002) Food (limited evidence), Sun *et al.* (2009)
	Changes in consumer tastes that lead to unexpected changes in demand for a company's product	Miller (1992), van der Vorst *et al.* (1998)	van der Vorst *et al.* (1998): Food (limited evidence)
	Irregular or sporadic events that lead to uncertainty, e.g. sports events	Bartezzaghi and Verganti (1995)	Bartezzaghi and Verganti (1995) Telecommunications (limited evidence)
U8. Demand amplification	Demand signal processing that leads to unusually high stock levels in the upper regions of the supply chain	Lee *et al.* (1997), Wilding (1998), Dejonckheere *et al.* (2003), Blecker	Lee *et al.* (1997): Computer, consumer goods and retail, Dejonckheere *et al.*

(*continued*)

Appendix 1. Continued.

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
		et al. (2005), Prater (2005)	(2003):Consumer goods and retail
	Rationing game that stimulates customers to order more units than they need, this lead to uncertainty of actual end-customer demand patterns.	Lee *et al.* (1997), Wilding (1998)	Lee *et al.* (1997): Computer and automotive
U8. Demand amplification (contd)	Order batching policy, which obscures actual demand.	Lee *et al.* (1997), Wilding (1998), Geary *et al.* (2002)	Lee *et al.* (1997): Consumer goods and retail
	Price variations, e.g. discounts or promotions, that lead to unexpectedly high demand	Lee *et al.* (1997), van der Vorst *et al.* (1998), Wilding (1998)	Lee *et al.* (1997): Food and consumer goods, Wilding (1998): Retail industry
U9. Supplier	The timing of supply may be uncertain if the supplier is regularly unable to meet promised due dates	Davis (1993), Towill *et al.* (2002), van der Vorst and Beulens (2002), Sawhney (2006)	van der Vorst and Beulens (2002): Food Sawhney (2006): Electronics
	The quality of supplied product may vary, e.g. this may depend on the quality of the variable crop quality	Towill *et al.* (2002), van der Vorst and Beulens (2002), Sawhney (2006)	van der Vorst and Beulens (2002): Food Sawhney (2006): Electronics
	The availability of supply may be uncertain	Miller (1992), van der Vorst and Beulens (2002)	NA
U10. Parallel interaction	General parallel interaction issue among suppliers that supply different products to a company, e.g. cross-docking issues	Wilding (1998), van der Vorst and Beulens (2002), Prater (2005), Manuj and Mentzer (2008)	van der Vorst and Beulens (2002): Food
U11. Order forecast horizon	General order forecast horizon issue, i.e. the longer the horizon, the larger the forecast errors, and hence there is a greater demand uncertainty	Muckstadt *et al.* (2001), van der Vorst and Beulens (2002), van Donk and van der Vaart (2005)	van der Vorst and Beulens (2002) Food (limited evidence)
U12. Chain configuration, infrastructure and facilities	The geographic areas covered by the supply chain, such as difficult terrain or long distances.	Prater *et al.* (2001), van der Vorst and Beulens (2002), Manuj and Mentzer (2008)	Prater *et al.* (2001): Electronics
	Uncertainty in network relationships caused, for example, by differences in culture, processes and strategy	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food (limited evidence)
	The availability of dependable communication that leads to delayed processes and reduced flexibility	Miller (1992), Prater *et al.* (2001),	Prater *et al.* (2001): Electronics
	The availability of dependable transportation infrastructure that leads to delivery process disruptions	Miller (1992), Prater *et al.* (2001), Rodrigues *et al.* (2008)	Prater *et al.* (2001): Electronics
U13. Environment	Political stability, i.e. political instability in a country that has a serious impact on supply-chain processes	Miller (1992), Andreas and Ulf (2004)	NA
	Government regulation, when it is often changed, it may disrupt company plans, e.g. a new trade barrier for imported raw material	Miller (1992), van der Vorst and Beulens (2002), Christopher and Peck (2004)	NA

(*continued*)

Appendix 1. Continued.

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
	Macroeconomic issues, e.g. price inflation, fluctuations in exchange and interest rates, may press a company to change its plan, e.g. switch to local suppliers in case of an unfavourable exchange rate	Miller (1992), Christopher and Peck (2004)	NA
	Issues in a society, for, e.g. social unrest, may lead to violence, causing inability to run normal supply-chain operations in the affected area	Miller (1992), Andreas and Ulf (2004)	NA
U13. Environment (contd)	Competitor behaviour, e.g. a competitor may unexpectedly launch a new product to the market that forces a company to revise its supply-chain plans	Miller (1992), van der Vorst and Beulens (2002), Andreas and Ulf (2004)	NA
U14. Disaster	Natural disaster, e.g. earthquakes, hurricanes, and storms, that has a great impact on the supply-chain processes	Miller (1992), Zsidisin *et al.* (2000), Christopher and Peck (2004), Kleindorfer and Saad (2005)	Kleindorfer and Saad (2005) identified the supply-chain issues caused by Hurricane Andrew in 1992, the Kobe earthquake in 1995, and the Taiwan earthquake in 1999

Appendix 2. Profile of uncertainty-management strategy.

Source of uncertainty	Dimension	Strategy	Literature
U1. Product characteristic	Product specification	C1. Postponement	Product-development postponement, e.g. make decisions for specifications that are certain while postponing other specifications until better information is available (Yang *et al.* 2004, Yang and Yang 2010)
	Packaging characteristics	NA	NA
	Product life cycle	R6. Shorter planning period	Implementation of continuous replenishment to achieve physical efficiency in terms of enough stock to cover demand and sufficient time to sell off the excess stocks in case of end of product life (Fisher 1997)[a]
		C2. Volume/delivery flexibility	Application of strategy where products can be quickly produced and have short delivery lead times to retailers, e.g. in fashion markets with short product life cycles (Childerhouse and Towill 2003), volume flexibility to cope with high sales variations caused by short product life cycles in the computer industry (Gerwin 1993)[b]
	Perishability of products	R3. Process performance measure	Reliability improvement, e.g. in terms of production quantity and quality, e.g. the use of air-conditioned transportation and restricted storage time to prevent quality decay for perishable products (van der Vorst

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
			and Beulens 2002)[a] (*Reduction of food wastes*)
	Product variety offered	C1. Postponement	Develop the modularity of product variants to allow variety to be created at the final assembly, this may enable process standardisation while maintaining product variety (Ulrich 1995, Lee 2002)[b], Sun *et al.* (2009)[a] (*Increased responsiveness to end-customer demand*)
U2. Manufacturing process	Machine breakdowns	R3. Process performance measure	Proactive maintenance to maintain machine performance (Geary *et al.* 2002)
		C2. Volume/delivery flexibility	Process standardisation in multiple manufacturing facilities to cope with process disruptions (Sheffi and Rice 2005)[b]
		C3. Process flexibility	Utilising multi-skilled workers and general-purpose machines so that work can be transferred to other capacity groups (Sawhney 2006)[a]
		C4. Customer flexibility	Delay delivery to flexible customers (Sawhney 2006)[a]
		C6. Strategic stocks	Increase inventories (Davis 1993)
	Variable process yield and scrap-rates	R1. Lean operations	Quality levels improvement by implementing waste elimination principles (Mason-Jones and Towill 1998, 2000, Muckstadt *et al.* 2001)[a] (*Reduction of production cost*)
		R2. Product design	Better manufacturing processes by changing product designs (Davis 1993)
		R3. Process performance measure	Total quality control approach (Davis 1993)
	Changes in employee productivity	C3. Process flexibility	Coping with labour absence by utilising multi-skilled workers and working overtime. (Sawhney 2006)[a]
	Accidents	C3. Process flexibility	Multi-skilled workers and/or general-purpose machines to maintain process continuity (Sawhney 2006)[a]
U3. Control/chaos uncertainty	Small sales order is small compared with batch sizes	R6. Shorter planning period	Shorter planning periods may help to reduce issues in manufacturing planning systems that use batch size requirements (Wilding 1998, van der Vorst *et al.* 1998)
	Chaos resulting from supply-chain control systems	R1. Lean operations	Implementation of a manufacturing strategy where products are produced only after receiving real orders from customers (Wilding 1998, Geary *et al.* 2002)
		R4. Good DSS	Control systems (Mason-Jones and Towill 1998, van der Vorst *et al.* 1998,[a] Muckstadt *et al.* 2001) (*Reduction of inventory level and increased product freshness*)
		R6. Shorter planning period	Shorter planning periods help in maintaining accurate information (van der Vorst *et al.* 1998, Wilding 1998)
	Inaccurate or poor reports from supply-chain partners	NA	NA
U4. Decision complexity	Different goals across functional departments	R5. Collaboration	Improved coordination and alignment across functional departments (Helms *et al.* 2000,[b] Charu and Sameer 2001)[a]

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
			Co-ordination and negotiation to solve conflicting goals (Charu and Sameer 2001)[a]
		R7. Decision policy and procedures	Redesign of decision procedures to eliminate unnecessary process steps (van der Vorst *et al*. 1998)
		C11. Quantitative techniques	Use multiple objective dynamic programming or linear programming (Prater 2005)
	Capacity constraints	R4. Good DSS	DSS in which all elements in the supply-chain are considered (Muckstadt *et al*. 2001)
		C11. Quantitative techniques	Goal programming or fuzzy dynamic programming (Prater 2005)
	Uncertainty in long range strategic planning	C11. Quantitative techniques	Traditional ranking procedures, neural networks, genetic algorithms and chaos theory (Prater 2005)
	Administrative issues and decision policies	R7. Decision policy and procedures	Redesign of decision policy and procedure to eliminate unnecessary process steps (van der Vorst *et al*., 1998)
U5. Organisation/behavioural issues	General behavioural issue	R3. Process performance measure	Linking of employee performance objectives with supply-chain objectives (van der Vorst and Beulens 2002) (*Reduction of process disruptions*)
		R7. Decision policy and procedures	Eliminate unnecessary decision process steps to reduce human-related issues that occur in lengthy administration processes (van der Vorst *et al*. 1998)
	Internal politics	No strategies proposed	NA
U6. IT/IS complexity	IT/IS system unavailability	R7. Decision policy and procedures	Implementation of stringent audit procedures and monitoring of computer usage (Bandyopadhyay *et al*. 1999). (*Increased customer satisfaction*)
		R8. ICT system	Backup systems and procedures: until the IT/IS system becomes available (Bandyopadhyay *et al*. 1999)
			Virus-prevention and firewall software (Bandyopadhyay *et al*. 1999, Greg 2006)
			Employee education, to reduce system misuse (Bandyopadhyay *et al*. 1999, Greg 2006)
	Data/information security issues	R7. Decision policy and procedures	Restricting access to the IT/IS system (Bandyopadhyay *et al*. 1999)
		R8. ICT system	Secure IT/IS system, such as, data encryption and recognition systems (Bandyopadhyay *et al*. 1999)
	IT/IS system performance	No strategies proposed	NA
U7. End-customer demand	Seasonal demand variability	R9. Pricing strategy	Marketing activities such as price promotions (Miller 1992) and (Gupta and Maranas 2003)
		C1. Postponement	Produce at a later time closer to the confirmation of customer orders (Fisher 1997)[b] (Mason-Jones and Towill 2000, Prater *et al*. 2001, Yang *et al*. 2004)
		C2. Volume/delivery flexibility	Flexibility in terms of volume of production (Gerwin 1993)
		C6. Strategic stocks	Inventory buffers (Wilding 1998, Helms *et al*. 2000, Towill *et al*. 2002, van Donk and van der Vaart 2005)

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
		C8. ICT System	To facilitate information sharing (Mason-Jones and Towill 1998)[b] (Towill and McCullen 1999, Prater 2005). (*Reduction of cost, increased responsiveness to end-customer order*)
		C9. Lead-time management	Loose delivery dates increase production flexibility (Prater *et al.* 2001)[a]
		C11. Quantitative techniques	Advanced forecasting techniques (Davis 1993).
	Changes in consumer tastes	R2. Product design	Introducing new products to match market leader offering and change market equilibrium retaining current customer base (Miller 1992).
	Irregular or sporadic events	C11. Quantitative techniques	Implementation of a forecasting technique to calculate overplanning requirements (Bartezzaghi and Verganti 1995). (*Reduction of production cost, increased fill rate*)
U8. Demand amplification	Demand signal processing	R1. Lean operations	Elimination of echelons and functional interfaces to reduce time delays and information distortion (Towill and McCullen 1999)[b]
			Application of time compression of both order information upstream and product transfer downstream to reduce distortion of information and enable effective material flow, which then reduces demand amplification (Mason-Jones and Towill 1998, 2000, Towill and McCullen 1999) (*Reduction of production costs*)
		R5. Collaboration	Information sharing and tight coordination to enable synchronised planning (Lee *et al.* 1997, Lee 2002)[a] (*Reduction of inventory level, removal of short term fluctuations in customer orders*)
		R6. Shorter planning period	To overcome the bullwhip effect, which is influenced by long replenishment lead times (Lee *et al.* 1997)
		R8. ICT system	To facilitate information sharing e.g. electronic data interchange (EDI) systems (Lee *et al.* 1997, Mason-Jones and Towill 1998, Towill and McCullen 1999)[b]
		C1. Postponement	To prevent over-reactions to short-term fluctuations in demand (Mason-Jones and Towill 2000, Prater *et al.* 2001, Yang *et al.* 2004). However, it may be costly to create this flexibility (Prater *et al.* 2001). (Increased responsiveness to short term demand fluctuation, may increase cost)
	Rationing game	R5. Collaboration	Manufacturer shares production plans and inventory with downstream supply-chain partners to reduce motivation for gaming (Lee *et al.* 1997)
			Restricting buying flexibility through commitments and contracts, in terms of order quantity (Lee *et al.* 1997)
	Order batching policy	R8. ICT system	The necessary requirement for order batching is reduced by utilising EDI (Lee *et al.* 1997) (*Reduction of ordering cost*)
		C7. Collaboration	Information sharing to enable the manufacturer plan independently rather than using

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
			an order batching forecast from the retailer (Lee *et al.* 1997)
	Price variations	R9. Pricing strategy	Pricing strategy to reduce the fluctuations caused by price variations (Lee *et al.* 1997).
		C7. Collaboration	Customers communicate plans that are out of the ordinary, e.g. sales promotions that are likely to increase the demand rate temporarily (Lee *et al.* 1997, Muckstadt *et al.* 2001)
U9. Supplier	Timing of supply	R1. Lean operations	The extension of 'Lean Thinking' approach with suppliers (Mason-Jones and Towill 1998, 2000) (*Reduction of inventory cost*)
		R5. Collaboration	Vertical integration (Miller 1992)
			Contractual agreement, preferably long-term contract, with suppliers to guarantee delivery of raw materials (Miller 1992)
			Work closely with suppliers, e.g. in terms of collaborative planning, and alerting each other of any potential supply disruption (Lee 2002, Christopher and Peck 2004)[b]
		R8. ICT system	To track and communicate material movement in order to anticipate problems (Sawhney 2006)[a]
		R10. Redesign of chain configuration and/or infrastructure	Building factory closer to suppliers (Bhatnagar and Sohal 2005)[a]
			Outsourcing logistics and using supplier hubs to enable more reliable transportation modes (Davis 1993, Lee 2002)[b] (*Reduction of logistics cost*)
		C5. Multiple suppliers	To enable flexibility in terms of sourcing (Miller 1992).
			However, managing and using multiple supplier may increase cost (Lee 2002, Sheffi and Rice 2005).
		C6. Strategic Stocks	A major reason for an organisation to carry stock (Towill *et al.* 2002)
	Quality of supplied product	R5. Collaboration	Vertical integration (Miller 1992)
			Contractual agreements, where specific quality measures are included in the agreements, are able to protect against any quality issues (Miller 1992)
		C5. Multiple suppliers	To enable organisation to source from different supplier in case of quality issues (Miller 1992)
			Buying from different supplier may increase cost (Lee 2002, Sheffi and Rice 2005)
		C6. Strategic stocks	Inventory to ensure delivery of product to customer on promised date (Davis 1993, Towill *et al.* 2002)
	Availability of supply	R5. Collaboration	Vertical integration for control supply volumes required (Miller 1992) Contractual agreements which include guaranteed volume of supplied products from supplier (Miller 1992)
			Close coordination to alert manufacturer regarding potential supply problems and work together to find solution to the problem (Christopher and Peck 2004)

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
		R8. ICT system	New supplier ICT system to track the movement and usage of their materials and improve volume flexibility (Sawhney 2006)[a]
		C5. Multiple suppliers	To cope with quantity of supplied products (Lee 2002)[b] Buying from different supplier may increase cost (Lee 2002)
		C6. Strategic Stocks	To cope with uncertainty related to the volume of supplied product (Towill *et al.* 2002)
U10. Parallel interaction	General	R1. Lean operations	The reduction of partners involved in a supply-chain potentially reduces problems related to parallel interaction, this leads to increased responsiveness to customer order (van der Vorst and Beulens 2002)
		R5. Collaboration	Good coordination among chain partners, for example in terms of inbound and outbound logistics (van der Vorst and Beulens 2002)
		R8. ICT system	To exchange information to generate suitable plans and delivery schedules (van der Vorst and Beulens 2002, Prater 2005)
		C6. Strategic stocks	Increasing inventory to cope with problems of late delivery of a rogue supplier (Wilding 1998, Prater 2005)
U11. Order forecast horizon	General	R6. Shorter planning period	Increased frequency of deliveries, e.g. daily deliveries, to improve forecast accuracy (van der Vorst *et al.* 1998)[a]
		R8. ICT System	Computer assisted ordering (CAO), which helped a distribution centre to manage stock levels at retailers, enabling short information lead times (van der Vorst *et al.* 1998)[a]
U12. Chain configuration, infrastructure, and facilities	Geographic areas	R1. Lean operations	Reduction of the number of suppliers that leads to less chance of scattered suppliers across the geographical area, hence, reduction of problems (van der Vorst and Beulens 2002)
		R10. Redesign of chain configuration and/or infrastructure	Build production facilities closer to suppliers and customers, this helps to reduce shipping time, both from the suppliers and to the customers, hence a shorter production time and better responsiveness to customer orders (Davis 1993)[b] Consolidating warehouses and outsourcing logistics which enable a better schedule of delivery and reduction of transportation costs (Prater *et al.* 2001)[b] (*Reduction of transportation cost*)
		C2. Volume/delivery flexibility	Flexibility in terms of volume and lead time (Prater *et al.* 2001)
	Network relationships	R10. Redesign of chain configuration and/or infrastructure	Align employee incentives with supply-chain objectives and reduce the number of human interventions needed for a supply-chain transation (van der Vorst and Beulens 2002).
	Communication	R8. ICT system	(EDI system to provide a dependable communication with suppliers and customers, this leads to better customer responsiveness (Prater *et al.* 2001)

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
	Transportation infrastructure	R10. Redesign of chain configuration and/or infrastructure	Outsourcing of transportation and distribution to a 3PL provider which enables effective delivery schedule and efficient operation of transportation and distributions (Prater *et al*. 2001)[b] (*Reduction of logistics cost*) Asking suppliers to transport goods to the factory because of their better know-how regarding local transportation modes and customs, this leads to reduction of inbound transportation cost although some delays may occur (Prater *et al*. 2001)[b]
		C2. Volume/delivery flexibility	Flexibility in terms of volume to compensate for slow outbound transportation (Prater *et al*. 2001)
U13. Environment	Political stability	C10. Financial-risk management	Purchasing insurance (Miller 1992)
	Government regulation	R5. Collaboration	Government lobbying in order to change laws, regulations, and trade restraints. Successful lobbying may bring about more predictable government regulation (Miller 1992)
	Macroeconomic issues	C2. Volume/delivery flexibility	Availability of production facilities in many countries to enable flexibility to temporarily switch production from one country, which is less affected by macroeconomic issues, to other countries (Tang 2006)[b]
		C10. Financial-risk management	Exchange rate risks could be managed by using financial hedging. This would prevent financial losses caused by unexpected fluctuation of exchange rate (Miller 1992) (*Reduction of financial losses*)
	Societal issues	C10. Financial risk management	Purchasing insurance (Miller 1992)
	Competitor behaviour	R5. Collaboration	Horizontal mergers and acquisitions to control competitive uncertainties (Miller 1992) Oligopolistic coordination with the industry leader where business competitors work together to stabilise the market and reduce uncertainty, e.g. in terms of agreed prices and product specifications (Miller 1992) It is reasonable to assume that the practice of oligopoly will increase profit and flexibility in the chain, although the study by Fisher (1997) suggested it has a negative impact on customer satisfaction
U14. Disaster	Natural disaster	C1. Postponement	A postponement strategy, based on modular production processes, to enable production of a products using alternative components (Tang 2006)[b] (*Reduction of production delays*)
		C2. Volume/delivery flexibility	The availability of production facilities in multiple location or multiple countries would enable an organisation to cope with natural disasters because customer orders can be served by other production facilities, which are not affected by the disaster (Kleindorfer and Saad 2005)
		C4. Customer flexibility	Enabling customer flexibility with suitable incentives may increase customer

(*continued*)

Appendix 2. Continued.

Source of uncertainty	Dimension	Strategy	Literature
			satisfaction and sales during the disruption period (Tang 2006)[b] (*Reduction of customer dissatisfaction*)
		C5. Multiple suppliers	To enable continuous supply when a disaster disrupts the main supplier (Tang 2006)[b] (*Reduction of customer dissatisfaction*)
		C6. Strategic stocks	Carrying stocks of raw material and products helps to ensure production and delivery to customers when disruption occurs (Tang 2006)[b]
		C7. Collaboration	Coordination in terms of early warning and mutual assistance during the disruption period to prevent major financial losses (Kleindorfer and Saad 2005)
		C10. Financial-risk management	Insurance (Miller 1992)

Note: Text in italics: impact on performance.
[a]With empirical evidence.
[b]With examples from secondary data.