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Environmentally responsible inventory models: Non-classical models for a non-classical era

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ABSTRACT

Mathematical models of inventory typically include the three inventory associated costs of surplus, shortage and ordering. These classic inventory models are then analysed so as to choose inventory parameters that usually minimise the total cost of operating the inventory system being investigated.

Unfortunately, classic inventory models do not provide a meaningful basis for analysing many real and increasingly important practical inventory problems and situations. It is therefore not surprising that over recent years, several authors have discussed these issues in broad terms and suggested that a new paradigm needs to be developed.

This paper develops some specific aspects of this discussion. In particular, the paper identifies a range of inventory problems that are not covered appropriately by traditional inventory analysis. One of these is to design responsible inventory systems, i.e. systems that reflect the needs of the environment. The paper then examines the importance of inventory planning to the environment in greater detail. For example, packaging is important, not only because of its costs and the protection that it provides to the inventory items, but also because of its eventual effects on the environment in terms of the use of resources and potential landfill. For similar reasons, waste, which can result from poor inventory management, is highly important. The location of stores is important because location affects transport costs. Thus the influence of the secondary aspects of most inventory models; packaging, waste and location are important but, even more important are the inter-relations with the total system. In particular, the location of the manufacturing plants and the effect that inventory planning has on the logistics chain, potentially have considerable environmental implications. Inventory is part of a wider system.

However, until the cost charged for an activity reflects the true environmental cost of that activity, it is likely that decisions will be made on the basis of erroneous data. In that situation, we are faced with either determining the environmental cost of specific actions or to use environmental costs that are somewhat contrived; in which case it may be more sensible to use very different performance measures and models. The paper discusses these ideas and ways in which inventory policies may reassure us with our environmental concerns.

1. Introduction and context

Man has dealt with inventory issues ever since he started to utilise the resources of the planet. However, inventory arises in many different situations and so it is unlikely that the same inventory planning and control considerations will apply equally to all categories.

Inventory management has been a focal research area in operations research/management science, production and operations management, and industrial engineering for many years. The first mathematical treatment of inventory systems was the economic order quantity (EOQ) model developed by Harris in the 1920s (Harris, 1913/1990). Interestingly, almost a century after its introduction, the EOQ is still being studied and extended by academicians. Major advances in understanding inventory problems took place in the 1950's and 1960's (e.g., Whitin, 1953; Arrow et al., 1962; Hadley and Whitin, 1963) with the emphasis on satisfying the needs of manufacture, logistics, etc. These classic inventory models include mathematical models that take account of surplus, shortage and ordering costs and are used to determine inventory parameters such as the re-order level (ROL) and re-order quantity (ROQ). The models are particularly applicable to operational planning for retailing, wholesaling and manufacturing stocks. However, as markets became competitive, dynamic and complex, inventory management also became more complex (Bonney, 1994) and market conditions have been changing more

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quickly than researchers could respond. Most inventory models are still confined to the classical cost analysis approach but the accuracy of the input parameters for these models is frequently uncertain. Some researchers (e.g., Bonney et al., 2003) examined some of the variables that are being affected by the dynamic environment in which companies operate and suggested that inventory models need more development and that parameter values are likely to change as a result. Recently, other researchers (e.g., Chikán, 2007) have moved away from classical inventory management by thinking that inventory should have an active rather than a passive role.

In addition to stocks that are needed for manufacturing, logistics, etc., inventory is needed for constructs such as health systems, military systems and organisations for humanitarian relief. Inventory planning of items such as decontamination units and medical supplies may be needed to deal with the potential consequences of terrorism. For health, of course there are many predictable problems but there is also the risk of new diseases and pandemics that could lead to great difficulties about what to do. For example, if, as many people predict, we may soon be hit by a new virulent strain of influenza then, even with the know-how and production facilities, how would one estimate how much vaccine should be made and then managed, to protect against the uncertain risk? With even more uncertainty, how does one plan to provide humanitarian relief for other rare but devastating situations arising, say, from an earthquake, a tsunami, or a military conflict? In some of the above situations, there will be a low but unknown probability that a specific event will occur. There will also be uncertainty about the timing. The risk levels are difficult to ascertain and the potential consequences may be severe.

Environmental problems are an area of steadily increasing concern and this paper examines the relation of inventory to the environment and, in particular, whether it is possible to create environmentally responsible inventory planning systems. It is suggested that in order to understand how to create such systems it is likely that further theoretical developments will be required and that there may be a need to develop methods that will determine inventory levels based on measures other than cost. Realistic costs are difficult to calculate even with the classic models (Jaber, 2009) but are virtually impossible with unusual and potentially catastrophic events. Also, and more importantly, models based on unreliable costs can be very misleading (e.g., Woolsey, 1990; Jones, 1991). However, potentially the most misleading aspect is that many of the model assumptions may not be realistic. Additionally, using cost minimisation as a performance measure is unlikely to give sufficient importance to meeting users' and society's requirements. Generalising to consider models in terms of utility may be intellectually satisfying but leads to equally difficult problems of measurement.

In order to derive their inventory parameters, stock items are generally considered independently. Frequently however, because there are interactions, the overall performance of an inventory system may not be the sum of the performance of individual items. For example, ordering some items may reduce the cost of ordering other items from the same supplier. Also, if an ordered item is manufactured using the same resources as other items, then the lead times chosen for some items may affect other lead times by changing queue priorities. Interactions arise also when several items of stock are needed at the same time e.g. for certain assembly operations. In that case, what is the shortage cost of a single item and is it the same if two items are short? Partial solutions, almost certainly non-optimal, to some of these problems are provided by Murdock's coverage analysis (e.g., Lewis, 1970), scheduling by load control (Wiendahl, 1995), and other production planning methods such as JIT, MRP, MRP II, OPT and period batch control (Burbidge, 1996). However, each planning method affects the ordering quantities (e.g., Johnson, 1986; Ptak, 1991; Voss, 1995; Miltenburg, 1997) but the quantities are generally unrelated to cost modelling.

Ideally, the OPT principle of using operational measures that are consistent with the strategic needs of the overall systems should be used. As an example, some studies suggest that the operational measures of throughput, inventory and operating expense are consistent with the strategic measures of profit, return on investment and cash flow (e.g., Fox, 1982; Kaplan, 1983; Gupta et al., 2002). Unfortunately however, many organisations appear to display little consistency between operational performance measures and strategic measures and so the system performance (the strategic measure) is not the sum of the parts (the operational actions). As Sprague (2002) mentions, even if valid models are derived, the different parameters in inventory models are not usually under the control of the same manager and so other inconsistencies can arise.

If there are these difficulties with situations that are not too far removed from the underlying classic model assumptions, it may be that there would be advantages in deriving inventory models based on metrics other than cost. This paper suggests that performance measures should encourage the positive aspects of holding inventory, such as providing flexibility, providing resources that allow things to be made, acting as a buffer and satisfying demand immediately but, at the same time, should act to reduce the negative implications of holding stock. Hence, to give inventory planning an environmental emphasis requires that performance measures should encourage 'environmentally good' activities and discourage 'environmentally bad' activities. Some possible ways of doing this are now examined.

2. Some current environmental problems

The world faces many environmental legacies. These include how to deal with greenhouse gases that have already been emitted into the atmosphere, how to reduce emissions that are still occurring and what to do with resources and waste products that have been used and then dispersed into landfill sites or just left to decay (or not). There are also many potential problems in the pipeline. The world has been using rain forests to supply wood and changing land use to produce soya for feeding animals. Large amounts of heavy metals such as lead have been released and dispersed into the environment from industrial processes, from using lead based paints (now mainly stopped) and from driving cars with anti-knock lead additives (now also mainly stopped). Mercury entered the fish food chain in Japan (e.g., Vallee and Ulmer, 1972; Gårdfeldt et al., 2003). Agricultural procedures have become much more intensive and depend on the use of large quantities of fertilisers for plants and antibiotics for rearing animals. A new disease; mad cow disease (BSE), resulted from changing feeding methods without considering the possible implications (e.g., Uzogara, 2000; Lindgreen and Hingley, 2003). Large amounts of chemicals and long lasting pesticides including organo-phosphates (e.g., Pimentel et al., 1992) have been released into the environment and may create long term problems (e.g., Levine, 2007).

From other causes (testing of atomic weapons and from the peaceful use of atomic energy) we have released long lasting radioactive waste into the environment. Nuclear power plants have created radioactive waste that will last thousands of years and we do not know where to put it (e.g., Krauskopf, 1988; Ringius, 1997; Dijkgraaf and Vollebergh, 2004). Non-radioactive but equally pernicious is dioxin, a chemical that has been released and still is, but to a lesser extent, from some industrial processes such as producing 'clean' solid fuel and from some waste processing plants. Plasticisers are used to provide flexibility to many items including plastic pipes e.g. for fish tanks. These chemicals are oestrogen like substances that can feminise the recipients of the water such as the fish in the tanks (e.g., Hurst and Sheahan, 2003). There is some concern about whether these hormonal substances, also arising from the use of contraceptive pills, and which may exist in very small quantities in some drinking water, are a health risk (e.g., Yang et al., 2006). Many other examples could be cited. However, the underlying problem is that every year thousands of new products are introduced and new substances released into the environment. These may provide short term gain but also they may have long term adverse effects, the reasons for which may be understood only many years afterwards (e.g., Sanderson et al., 2004; Bhuie et al., 2004). Often policies are changed without adequate testing and so consequential effects may only be identified after items have been produced on a large scale. More systematic piloting of proposed actions, perhaps based on the US procedures for certifying drugs by the FDA or the Swedish requirement for certifying new workplaces, may be a useful basis for introducing new substances.

As countries have developed, life styles have also changed. For example, the location of shops and houses and the means of travel to work have changed, making many people in the developed nations dependent on using a car. Our cities have continued to grow in size. Villages close to cities have become the new suburbs but are often without facilities such as shops. This increases the dependence of many people on a car for everyday quality living and it is hard to undo this voluntarily created social change (e.g., Blundell, 2003; Odum and Odum, 2006).

It is clear that planning is important when we make major changes and the planning process needs to take account of long term effects. Specifically, can we plan inventory so as to contribute to improving the world's environment? As always the key questions are the interrogatives; what do we stock, where do we store items, when and how much do we order and, perhaps most importantly, why are we using these items and how do the different choices affect the environment? As inventory is always with us, can we maximise its usefulness? Can we plan and control it so that it helps to improve the world and can we minimise its adverse effects?

3. Inventory: some of its benefits and problems

The starting point for the discussion is that a large number of inventory problems do not match the classic inventory model; in particular and as indicated in the introduction, health, military systems and humanitarian relief appear to be in this category. Secondly, most stocks are part of wider systems; and their control and the performance measures that are used for control purposes should relate to improving the total system. Thirdly, the environmental consequences of many actions may occur some time, often many years, after an activity takes place or substances have been released into the environment. This suggests that it would be useful to assess the consequences of activities by using measures that take account of time and that encourage reducing poor environmental effects. With some pollution e.g., phenol concentrations, nature can recover 'automatically' provided some threshold is not passed (e.g., Collins et al., 2005), whereas with others, e.g., hydrocarbon contamination, long term effects get worse (Danovaro, 2000). Some effects may be cumulative and sometimes they may be multiplicative. Fourthly, although the probability of some events occurring may be small, the consequences of their occurrence may be great.

The world's resources are finite. The world's population and its changing life style create many problems. These include shortages of important resources such as food and water that can lead to malnutrition and ill health, or shortage of oil that can lead to price rises. The risk of conflicts between nations increases. Some 'solutions' may create other problems e.g. using biofuels instead of fossil fuels, although environmentally cleaner, may mean that it is more profitable for farmers to use land to grow fuel than to feed people (e.g., Roetter and Van Keulen, 2008). This has been suggested to be one reason for rapidly rising food prices (e.g., Runge and Senauer, 2007). Currently, there are calls to evaluate the use of biofuels before any further transfer of land use is undertaken. Using limited resources and releasing waste into the environment can affect air and water quality and cause longer term problems. It is suggested therefore that planning for renewability is essential. Avoidance of wars is environmentally important as well as being necessary to avoid much human suffering. Indeed, anything that diverts priorities away from saving the planet must be avoided.

World problems, often inter-related, include (e.g., Midilli et al., 2005):

- Global warming.
- Large and growing populations and increasing life expectancy.
- Shortages of resources.
- Globalisation, based on cheap labour and transportation systems.
- Debt and debt repayment among nations.
- Unequal distribution of wealth between and within nations.
- Poor methods of conflict resolution between and within nations.
- Corrupt national leaders who can exaggerate the unequal wealth within a nation.
- Disasters such as tsunamis, floods, cyclones and earthquakes.
- Illnesses and potential spread of diseases, old and new, in animals and people (BSE, malaria, HIV, influenza, etc).

Many problems that arise as a consequence of population growth relate to the population's activities, their use of resources and their aspirations. Human activities including their travel, construction and food production are a major source of greenhouse gases. It is unlikely that the world can support a western life style for its population and some argue that there is the need for a massive shift to vegetarianism in order that more food can be produced. Nevertheless, many developing nations aspire to have more goods, electricity, western food and personal transport. Constraints arise from religious, ethnic and political intolerance and lack of human rights that can make the solution of problems more difficult and sometimes may make it difficult even to recognise and discuss a problem.

Population related problems include:

- The increasing wealth of many nations and people whilst alongside there is also increasing poverty.
- The acquisitiveness of many persons related to consumption, housing and consumer goods including personal transport.
- A shortage of land for growing food, for housing and schools, to provide clean water and sewage treatment, and for infrastructure needs such as roads, railways and airports, while retaining land for forests, wild life habitats and biodiversity.
- Sickness and the need for healthcare.
- A shortage of will, resources and know how to tackle the problems.

Activities associated with stock items include processing material to create the stock, transfer between stock locations, item use and disposal. In order that inventory planning and control can help the environment, stock performance measures should consider the inter-relationships of the inventory with the environment over the logistics chain. To examine these problems there is a need to identify the players involved, identify their roles and responsibilities, their activities and their inter-relations with the other players (e.g., Bonney, 2007).

4. A hierarchy of inventory players

Inventory is essential for human activities. Many groups, hereafter called the players, have an interest in inventories. This paper considers five categories of players, namely: international organisations, nation states, local governments, companies and other organisations, and individuals, described hierarchically as levels 1 to 5 respectively. All of the players operate broadly within the constraints set by themselves and the other players. The first four levels are human constructs. Between them, the five groups need to produce acceptable and effective inventory systems and environmental results. As a minimum, this requires defining the players' roles, their interfaces, and procedures determining what should be done. Time is a complicating factor as it takes time to learn, agree and implement proposals. Also it is difficult to determine whether and how adverse consequences will arise and, if they do, then how long it will take for them to manifest themselves. The roles and interfaces of the five players are indicated in Table 1 and summarised below. Further discussion on this topic appears in Bonney (2009).

Level 1, international organisations, set frameworks, co-ordinate actions, set agendas (such as Kyoto and its successors) and decide on targets within which nations, with agreement, will work. Greater co-operation with nations will be necessary because environmental effects such as global warming and water and air quality are extremely important and do not respect national boundaries. Problems relate to agreeing plans and ensuring that countries achieve what they set out to do (Stern, 2007).

Level 2, nation states, create the legal framework for their country, raise revenue through taxes, create infrastructures including for transport and for buildings and set environmental constraints relating to manufacture in terms of health and safety, materials, processes, solvent use, emissions and waste disposal. They could provide environmental information to raise the awareness and knowledge of their populations. In this sense they interact with all of the other players. Their interface with international organisations aims to balance the interests of their own citizens and enterprises with wider international needs. The transport infrastructure and its costing structure is relevant to the costs and energy use of enterprises (level 4) and of individuals (level 5).

Level 3, local governments, (states, counties, cities, boroughs, etc.) are an intermediate stage in a decision hierarchy between the government and the organisations and people that do things. They interpret national rules to take account of local conditions e.g. by setting planning constraints for housing and industrial developments, supervising building regulations, providing local amenities, collecting refuse, and generally being involved with all local services such as education, police, roads and local transport.

Level 4, companies and other organisations, are the main group that do things. Members plan and organise, make, stock and deliver items, teach, clean, provide health care, etc.

Level 5, individuals, mainly work in organisations. They also run their own lives, raise families, buy, use, consume and possibly waste items, and use energy to keep themselves warm or to get to places including their workplaces. Ultimately it is individuals in organisations who choose, buy, use and dispose of items made at level 4 within the constraints set by levels 2 and 3.

Virtually no inventory is held at the international level, level 1, except possibly some for humanitarian purposes. At level 2 there are reserves for a country's armed forces and probably some strategic stocks of food, oil, medicines and equipment reserves for services set-up to deal with accidents, fire fighting, etc. At level 3, there are mainly operational stocks to allow activities like street cleaning to operate satisfactorily. As, in principle, operational activities could be sub-contracted, these operational units and some military stocks could be considered as equivalent to level 4 organisations. Physical inventories are held mainly at the organisational level, level 4, and this level is the main focus of the following discussion. Most of the activities relevant to this paper are at level 4 where players at this level interact horizontally (suppliers, manufacturers and retailers). Although individuals (level 5) interact (upwards) with retailers only (level 4), retailers interact (downwards) with customers through collecting used items for recovery (repair, reuse, refurbish, remanufacture, or recycling). Activities like repair and reuse, for example, are greener than recycling as less energy is used and less waste created.

5. Inventory performance metrics including non-cost metrics

Inventory analyses should help us to understand the effects of holding stock. These analyses could contribute to decision making designed to improve environmental conditions at each level. Each category of player needs to define its inventory actions, which should be based on the beneficial and adverse effects that these actions would have on resource usage, investment required, etc. As far as possible, players need to avoid negative activities such as high energy usage, high resource usage, producing pollution and undertaking unsustainable activities. Actions should take account of interactions so that e.g. inventories should be considered

Table 1
A hierarchy of inventory players: their role and interfaces.

Player level	Player description	Typical example	Inventory holding	Main roles	Interfaces
1	International organisations	UN	None	Set agendas, coordinate and agree proposals, monitor actions	2
2	Nation states (Countries)	UK	Strategic stocks of food, energy and medicine	Balance Level 1 and national needs, develop infrastructures, legislate and fund activities	1, 3, 4, 5
3	Local governments	County, city	Very little	Administer locality consistent with legislation	2, 4, 5
4	Companies and other organisations	Manufacturing, retailing, NGO's, etc.	Materials, products, food, water, etc.	Provide jobs, create wealth and run their units	3, 5
5	Individuals	Citizens of the world	Housing, food domestic goods,	Use and consume items, Influence higher levels, pay taxes, vote	2, 3, 4

over the logistics chain (mainly level 4). Apart from possible deterioration and possible obsolescence most stock items do not change except when being made, modified or scrapped. Therefore, it is likely that interactions and factors such as travel, manufacturing efficiency, etc., will be environmentally more important than the stock itself. Legislation (level 2) could influence inventory waste (mainly level 4) by making items obsolescent rather than obsolete. Legislation could influence also the location, time and, possibly health and safety constraints under which items may be manufactured, bought, consumed or otherwise used. How to determine the legislative agenda relating to each category of player is not discussed here.

To make environmentally appropriate decisions, organisations and persons need to be fully involved in the planning and operation of the logistics chain activities such as inventory, manufacturing and transport. A 'carrot' and 'stick' approach may be needed to encourage them. The carrot could be tax concessions for environmentally desirable activities; the stick could be legislation and increased taxes for undesirable activities. However, to decide what to do we need to know whether actions are 'good' or 'bad'. Metrics are needed to help assess that.

Flexible systems are required to meet the problems that arise as conditions change over time. The systems should encourage providers and users to identify developing needs quickly and guide their decision making. To achieve this, metrics are needed that identify and measure performance including the environmental effects of activities and how far these activities satisfy the needs of the hierarchy of players. Preferably, these performance measures should relate to total system performance. Individual satisfaction (level 5) should be improved and it may be worthwhile considering whether the systems could improve some human satisfaction measures such as health, happiness, flexibility and stability. Systems at levels 2, 3 and 4, e.g. related to transport and energy, need to be more responsible with respect to the environment. Nations and local governments at levels 2 and 3 want to produce appropriate legislation and rules that do not inhibit lower level activity but encourage environmentally responsible activities. Producers (level 4) need to know how to produce items in an environmentally good way that is consistent with the legislation particularly if that could be done inexpensively. Such production/inventory analyses should become much clearer once the environmental effects of activities are properly costed. Classical inventory models in general use cost functions related to the surplus, shortage and ordering costs of stock. Currently, the most commonly used inventory system objective is to minimise cost. However, as was indicated earlier, it is likely that non-cost metrics would be useful in many situations (e.g., Vokurka and Fliedner, 1995; Durden et al., 1999; Crilley et al., 2002). Metric categories that possibly could be used to determine inventory parameters include financial measures, inventory system (consisting of the stores, the computer system, the people employed, etc., over the logistics chain) measures, measures for the people that operate and use the system, measures for the recipients of the system (the customers), risk measures, measures for the environmental consequences of using the systems. Some possibilities for each of these categories are now examined. If the implications of using a chosen metric to analyse inventory systems are, after test, economically and environmentally satisfactory then the analyses will need to be converted into operational rules and potential users encouraged to adopt them.

Financial criteria and associated measures, traditionally used to derive parameters such as ROL and ROQ, will not disappear but will need supplementing. Such measures include:

- Minimise the total cost of surpluses, shortages and ordering. Traditional shortage models consider shortage costs as loss of profit plus loss of goodwill.
- Maximise profit and maximise utility.
- Other standard decision analysis metrics such as minimax losses and maximin profits.
- Investment appraisal methods that will provide appropriate returns on investment such as IRR (Johnston, 1980), which may be used to determine safety stock by considering the value of the improved service that arises from investing in safety stock.

Inventory systems measures include:

- Minimise the cost of operating the system.
- System performance measured in terms of service, stock levels, etc.
- System robustness and system stability in response to changing demand patterns.
- The risk of operational failure of the system (see below).

Measures for the people who operate and use the inventory system include:

- Measures of system usability and operational simplicity. These could include facilities that encourage reduction and standardisation of the number of stock items, using visual control so that there are visual cues to back up the computer records, etc., and the provision of simple links to the rest of the chain (e.g., to trace progress on an order).
- Ease and clarity of the system operation to reassure the inventory controller.
- Measures that help to control service levels and costs to reassure senior managers.
- Appropriate service and return on the investment to satisfy the planning group.
- Appropriate communication mechanisms so that what the user wants and agrees (see next set of measures) is communicated to the system operators.

Measures for customers' satisfaction include service provision, design and construction quality, price competitiveness, etc. Apart from service level provision, inventory analysis has not explored potential user satisfaction deeply.

Possible inventory systems risks include: physical risks, not considered further here, such as systems failure because of fire or computer breakdown, secondly, individual item shortages e.g. occurring because of unexpected events, using an inappropriate system, poor item quality, late delivery, forecasting errors or poorly chosen safety stock levels, and, thirdly, environmental risks. Risk profiles could be non-linear to allow for small probabilities of extreme events e.g. having sufficient vaccine available to prevent or respond to an epidemic, sufficient military resources available to avoid losing a battle, etc. Sometimes, high stocks to meet unexpected demand may have advantages when the consequences of shortages could be severe. Decisions could then be weighted so that poor consequences become very unlikely.

Environmentally focussed metrics need to measure and present system performance in a clear and suitably motivating way. Environmental decision criteria for inventory have been considered very little but some aspects are now discussed.

6. Environmental inventory performance metrics

Section 5 suggested some metric categories that could be used to assess inventory performance. For intuitive and practical reasons, the authors have left usability and user satisfaction measures for future consideration. Among the financial and associated measures it is suggested that investment should be considered more broadly than in financial and risk terms only; it should also consider the environmental implications including its environmental return, possibly measured by the reduction in energy use, the reduction in transportation, etc. Indeed, because of their absolute nature, some thermodynamic measures may be appropriate. To assess system performance, service and stock level measures will continue to be important. When possible, characteristics with potential environmental implications such as the response and stability of the manufacturing/inventory system to various demand patterns should be measured.

Environmental problems are global. Although some locations may be more able to accept pollution e.g. impermeable rock may stop waste products leaching into the wider environment, problems are not, in general, eliminated by shifting them into someone else's backyard. Also, although politically some locations may be easier to choose because of low population density, or because the proposed location is already blighted or because that location lacks people power, a better approach is to reduce environmental problems by improved design, production and other activities. Better still would be to avoid environmental problems altogether.

To reduce resource usage and pollution, systems should (e.g., Cairncross, 1992; Kroon and Vrijens, 1995: Ravi et al., 2005; Blackburn et al., 2004; Kumar and Craig, 2007):

- Minimise stock holdings.
- Produce and use stock efficiently, e.g. by avoiding waste and smoothing production and demand fluctuations.
- Recycle rather than scrap items.
- Choose locations, routing, delivery frequency, etc. to reduce the transportation required.
- Find less damaging ways of transporting items.
- Design for repair, reuse and upgrade rather than for disposal.
- Encourage refurbishing of products.
- Choose item size and packaging so as to reduce packaging and transport.
- Avoid activities and use of materials that potentially could have major adverse environmental consequences.
- Assess energy expenditure.
- Consider whether anything could be used rather than wasted.
- Assess the effect of inventory decisions on the environment.

Inventory analysis should be considered over the logistics chain and include consideration of suppliers, manufacturing, storage locations and demand. Therefore, recent emphasis by investigators and practitioners to investigate logistics chains rather than individual stock locations would appear to be correct. As stocks are required over complete product life cycles, inventory should be considered in that context. Thus, any new framework for inventory studies would appear to require considering the inventory logistics chain over the product life cycle using agreed metrics that encourage better environmental activities and also take account of time. Specifically, the most important environmental metrics are probably those that could assess the environmental implications of producing, transporting and using the items and the environmental effects of running the inventory system. The objective of these metrics is to formally assess logistics chains and so help to produce economically sound judgements that the system is providing the service required and environmentally sound judgements that the environmental consequences are acceptable.

The environmental consequences of each stage of the product life cycle (Bonney, 2007), and how stock can help or hinder responsible design, manufacture, use and disposal of the product, should be considered. Stages of the product life cycle include: product design, process design, manufacturing and inventory control system design and implementation, physical manufacture including obtaining the material and parts, the manufacturing processes and the distribution of the product. Manufacturing and inventory system design includes producing, transporting, storing and delivering items. Each step needs to be considered in the context of the items' eventual use. Particular environmental considerations are resource and energy use of each activity performed. Specifically, energy use needs to be reduced and, when that is under the planner's control, less carbon based (coal, oil and natural gas) energy sources used. Product simplification, using appropriate tools such as value analysis and value engineering, while retaining functionality, can reduce the number of parts and hence the amount of stock required and thereby reduce resource usage.

Stocking policy includes choosing whether to make to order or for stock, deciding the service level provision, choosing stock locations, batch sizes and packaging, and dealing with waste and the disposal of obsolete items. Many items, particularly those with short lead times could be made available fairly quickly by e.g. using air travel. However, to a certain extent, there is a trade off between environmental effects and speed. It is suggested that metrics related to the environmental consequences of inventory activities should include the effects of:

- Reducing the complexity of the products.
- Reducing the lead time of the products.
- Changing the location of production, stores and even customers so as to reduce the likelihood of demand changes and potential waste.
- The time response, system stability and the levels of shortages and surpluses.
- Running the stores e.g. energy use, material use, emissions, and the efficiency of the technology used.

7. Implications

A major reason that organisations undertake activities is to save money or increase profit, or influence other important factors such as quality, delivery time or delivery reliability that are essential for competitiveness. Major influences on stock location and travel are tariffs, defined at level 1, taxation imposed at level 2 and exchange rates that are influenced by the international money markets and the economic health of the nation state, including borrowings, national policies and the balance between imports and exports. Despite the recent failure of the Doha negotiations, the current rules agreed at international and national levels e.g. with respect to tariffs have been designed to encourage and increase multinational trade. However, once environmental considerations are accepted as the first priority, the rules that are currently used may need to change so as to encourage environmentally good activities. Rule changes to improve environmental consequences and to reduce unnecessary travel will require co-operation between nations about taxation, tariffs and exchange rates. This will be difficult. Insensitive handling of this issue could create international disputes that would be difficult to resolve. Poor nations may require help to participate.

Level 4 stocks are held mainly by manufacturing, wholesaling, retailing and food companies. It is likely that there is a trade-off between where stocks are held and the amount of travel.

Environmental costs currently appear to be tipping rapidly towards encouraging producers of bulky and heavy products to produce and store items locally rather than to transport them from afar. This suggests that producers should gradually return from outsourcing to producing items locally or in house. Devices such as farmers markets that provide local food produce are receiving growing customer support and some supermarkets and restaurants are responding by selling local produce. Food inventories need to protect against seasonal production fluctuations. Similarly, stocks may need to be held by some manufacturers to protect against seasonal customer demand fluctuations. Manufacturing location could be affected by changes in transport costs but location is constrained also by skill availability. However, for some industries, such as IT and software development, production of artwork and some other knowledge based industries, faster and cheaper information transmission means that the location is more flexible.

Assessing the environmental consequences of the different inventory factors allows one to make decisions about which inventory system to use. In essence, this activity is an inventory audit that tries to assess what could and should be changed to improve the environmental impact. A typical set of questions and, by implication, answers are required, to identify the effects of:

- The amount of inventory held and the replenishment rules on inventory system performance?
- The number and location of stores on the travel and energy expended when transporting items to and from the stores?
- Inventory storage area design on the energy expended? Factors include comparing refrigeration, insulation and heating costs in a cold climate with alternative locations that may be warm. Storage and design also affect queuing times for transport access and internal transportation.
- The storage facilities (including protection by packaging or by controlling local temperature and humidity) on the amount of deterioration that will occur with different items?
- The need and use of packaging material and the consequences of its disposal?
- Waste and the consequences of its disposal? Reducing waste reduces energy expenditure and the use of other resources. This may imply that safety stocks and batch sizes should be reduced particularly towards the end of the product life cycle.
- Inventory location on the travel and energy expended by the staff working there?

Additionally, before moving on to more complex decision making it may be worth considering current anomalies such as:

- Tax is not charged on aviation fuel and so air travel is subsidised relative to road and rail.
- Bottled water is sold to countries that have perfectly good quality water on tap. Even more wasteful, bottled water may be sold between two such countries.
- Fish caught in the North Sea may be transported to China for processing into fish fingers before being returned to the UK.
- EU bio-fuel can receive a subsidy from the US that makes it cheaper for it to be processed in the US. This incidentally may put local processors out of business.

It is likely that if anomalies such as these can arise with simple products, it is virtually certain that similar problems will exist with many complex products.

Unfortunately, by the time that a factor is found to be important, it is often part of an established and profitable activity and so profit and political influences may sometimes intervene to ensure the status quo. Therefore there is a need to identify as many potential problems as possible before implementation. If the consequences of an inventory activity are known it may be possible to identify reductions or alternatives for those that have an adverse effect. Similarly, it is much more likely that potential environmental incidents such as spills, waste and write-offs can be avoided if they are identified early. This is more likely to occur if the polluter pays principle is adopted universally and backed by appropriate penalties.

Some views on waste, packaging and production organisation are now presented. Waste needs to be reduced. The JIT philosophy suggests that inventory is waste. In general, JIT systems use small batch sizes so that fewer items are in storage and in transit. This requires among other things designing items so that they require reduced set-up and locating suppliers close to manufacturing plants so as to reduce travel and associated CO_2 emissions. It could also mean having smaller stores. On the other hand, other things being equal, small batches mean more travel and more set-ups. Environmental priorities therefore change the economics of JIT methods and put even greater pressure on quick change over, having part suppliers close to the production units which in turn also should be near to the markets. More standardisation is advantageous. Smooth flow is better than intermittent flow in the sense that there is less stock waiting in a queue to be processed. The most straightforward JIT systems occur when items are produced continuously using batch sizes that may be considered to be either one in the sense of not waiting for the rest of the batch, or infinite in the sense of not requiring a new set-up. Such production is effectively process manufacture and, to achieve this, component items need to be available when they are required. In general, well designed continuous flow e.g. on a conveyor requires less packaging protection than when items are transported over long distances in small batches. However, JIT has allowed companies to have shorter product life cycles, which could lead to rapid technical or fashion obsolescence that encourages waste. Perhaps the next development will be to design high quality products with longer life cycles and to use JIT only when it is environmentally helpful.

Reconciling the competitive advantage from using short product life cycles with environmental needs will be difficult. Similarly, designing products so that refurbishment is financially viable is a technological challenge. Self assembly, such as with flat pack home assembly furniture, may provide a flexible way to achieve volume production, product variety and longer term refurbishment possibilities but will require more emphasis on design and quality.

The issues are complex. Packaging decisions and batch sizes each affect energy expenditure. Packaging can protect the packaged items, identify items, show the delivery destination and, sometimes, advertise and provide 'image' to an item. Although it may ease carriage, packaging rarely adds functionality to the product from the users' point of view. Sometimes, the cost of packaging and its disposal is more environmentally expensive than producing and using the product. If so, one wants as little packaging as is compatible with protecting the item from damage, deterioration and theft. In general, producing in larger quantities can require less energy per item, containers holding many items require less packaging per item and transporting larger quantities can reduce unit transport costs. Options such as local assembly of CKD items may save on transport but incur local production costs. Other factors to consider include; good design could provide possibilities for easier refurbishment, considering activities over the logistics chain can make savings, using approaches such as JIT and MRP to control production can influence batch sizes, the time taken to deliver items, the resources used and the stock levels. In summary, the organisation of production, the location of plants and depots and the batch sizes chosen, can influence transport needs and so will also affect the environment. Taking account of environmental costs as far as one is able can have a positive influence and awareness of the potential interactions can suggest where further knowledge is necessary.

8. Inventory systems, models and possible analyses

Modelling is an important tool for investigating complex problems such as the interaction between stock levels and the environment. Models that use only a few variables can indicate whether those variables have a positive or negative influence and, by doing so, may broadly show the influence that they may have in isolation and help to identify variables that need closer analysis. However, because of system complexity, models may not be a satisfactory basis for action by themselves; models optimised against one metric will in general not perform as well against another metric e.g. optimising on cost is unlikely to give the best environmental solution. For these reasons it may be advantageous to perform 'total' simulations and assess performance against many different measures such as cost, return on investment, service level, inventory turnover and labour requirements all of which are important in addition to some of the environmental metrics already listed and others to be discussed shortly.

Analyses that could lead to a greener environment include identifying the objectives of holding stock and then basing performance measures on the potentially good or bad environment effects of the inventory system. Performance related problems include:

- Identifying appropriate performance measures for these good and bad effects.
- Examining these measures over the complete logistic chains so as to identify realistic travel use, delays, and the variability that arises in the stock levels and shortages.
- Considering how best to build up stock at the start of the product life cycle when modifications are more likely and to determine end stocks based on potential shortages or wastage at the end of the product life cycle as demand declines.
- Producing an environmental ABC analysis of the environmental impact of stock.
- Categorising stock according to time related conditions such as functional and technical obsolescence, lead times and shelf life.
- Using the above classifications to determine how to control items.

Problems that could be analysed from an environmental point of view include:

- Identify the activities involved when deciding what items to stock and their location.
- Rework standard models based on using more environmentally friendly performance metrics. Although the analyses would appear to be straightforward but time consuming, the results are likely to require careful interpretation. Appendix A presents a simple model that illustrates some of these ideas.
- Examine the inventory implications of scheduling systems, particularly MRP.
- WIP levels influence manufacturing lead times and may be chosen to maximise the ROI (e.g., Bonney, 1982). Changed lead times can have environmental implications by affecting pipeline stock.
- Use knowledge of the demand characteristics to determine the risk of not using stored items.

A more important question is how to identify what is not known as it is that what will determine the focus of future research investigations. Bonney et al. (2003) considered a generalised concurrent engineering representation to identify the requirements on production and inventory so that they could be more responsive. Bonney (2007) extended these ideas by developing activity and research matrices to identify what we do and do not know within a concurrent engineering context expressed over the product life cycle. Environmental needs and inventory can be examined within the research matrix context.

9. Summary and interpretation of the paper

The paper has examined some possible environmental consequences of common activities and suggested that all functions within the product life cycle including inventory planning and control should be looked at from an environmental point of view. A simplified model was constructed to illustrate how, in principle, one could determine inventory parameters in an environmental context. This suggests that the parameters that we frequently use to determine inventory levels may need to be re-assessed. The main arguments that have been made in the paper are as follows:

Section 1 suggested that inventory is important and that there are many types of inventory problem and also suggested that there may be a need for some different (non-classical) forms of inventory analyses. Section 2 suggested that there are many environmental problems and that many of these relate to product production, product use and the changing life style of individuals. It was asked whether inventory actions could help to improve the environmental consequences of activities. Section 3 suggested that many environmental problems arise from the misuse of products but others are a consequence of the type of society that we have created. Increasing wealth and personal acquisitiveness combined with cheap transport have led to globalisation and high levels of consumption. Many items are scrapped for fashion or technological reasons rather than because they have ceased to function. On the other hand, many societies have gained by globalisation and it has allowed many countries to develop rapidly.

Section 4 introduced a possible hierarchy of players and suggested that operational use of inventories exists mostly at the company level (level 4) and at the individual level (level 5) where choices to purchase or use specific items are made. Companies and individuals each work within a strategic context that is broadly set at the nation state level (level 2). Section 5 examined inventory performance metrics related to finance, inventory systems and the people who operate them and the customers who use the system. Section 6 examined inventory environmental performance metrics. Both Sections 5 and 6 included some non-cost metrics. More importantly, Section 6 suggested that inventory analyses should:

- Relate to the complete logistics chain.
- Apply to the complete product life cycle.
- Be based on metrics that encourage better environmental activities.
- Take account of time.

Section 7 identified some implications of the earlier discussion and listed some questions that are in need of answers. Section 8 examined the possibility of using models to perform analyses. This cross referred to Appendix A that illustrates simplistically how one could develop and use inventory models to investigate some potentially adverse environmental effects, particularly related to travel. The results of the Appendix suggest ordering items in larger quantities less frequently than the traditional EOQ model thereby reducing transportation costs and consequent CO_2 emissions. Furthermore, these results imply that a cost benefit analysis could be developed where a joint society/firm benefit function arising from inventory is measured against a cost function. It was suggested that the most important thing was to identify what we do not know and to convert this ignorance into knowledge. This will require much further analysis. The discussion specifically suggests that effort is needed to reduce the amount of travel and to reduce the waste associated with holding stock.

Financial, usability and environmental metrics were selected from the performance measures identified in Sections 5 and 6. It appears likely that inventory models will need to be further developed and re-interpreted. Intuitively, stock locations may need to change to reflect increasing transport costs, there is likely to be more local independence and the arguments for globalisation may need some adjustment. With current policies, globalisation, populations and demand will almost certainly increase and so create many resource shortages, potentially leading to price rises. More worrying is the likely adverse environmental impact of many of our actions. Yet, despite that, it appears that financial effects such as rising prices are more likely to change attitudes and activities than exhortations or widespread environmental knowledge of say rising water levels. This is the argument for increasing taxes on undesirable activities and recent oil price rises suggest that price rises do change actions. On the other hand, many people may interpret price increases as profiteering on the part of large organisations or as a new way for governments to raise taxes rather than as an incentive to be more environmentally responsible. In short, good effects may be limited because rising costs could cause inflation and change wealth distribution and create an intense adverse political reaction among electorates.

Unless an economically feasible substitute energy source to fossil fuel becomes widely available, it is likely that increasing demand could lead to increasing fuel prices that could raise transportation costs so much that globalisation will face an apparent economic and social brick wall. The implication is that we may need to move towards longer product life cycles, encourage repetitive repair rather than disposal and operate small decentralized regional markets that are supplied by small to medium size local manufacturers. This may require altering our consumption behaviour, our marketing strategies and our pedagogy at schools. If this occurs, there will be inevitable social implications. It may loosen the grip of giant companies on wealth and encourage the creation of small businesses and jobs and provide a fairer distribution of wealth. Equally possible, a clear view of the needs could provide many new business opportunities that would be suitable for franchising or which a larger company could respond to more easily. Because it is easier for those with wealth to take advantage of the opportunities that go hand in hand with change, the transition period needs to be carefully handled so that those without much power do not suffer too much.

Much greater understanding will be needed so that the inventory professional can play a full and constructive part in what almost certainly will become an environmental revolution that links with our current computer age. It is obvious that changes will provide business opportunities that the world will need to exploit. In general, those organisations that respond positively will have a commercial advantage over organisations that have a more sluggish response. Some preparation can be done now in areas that are also good cost-wise such as product simplification, developing reverse logistics approaches, developing systems that can be physically separated by using the power of improving communications and, possibly by disseminating knowledge that already exists but also by building up knowledge, developing research and implementation methodologies that should involve governments, consultants and researchers.

The scale, detail and timing of the conjectured scenarios outlined above are difficult to predict. However, it is clear that greater knowledge is required and that there is a requirement for flexible inventory systems that can respond in an environmentally responsible manner to changes as they occur.

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Appendix A. Embracing the EOQ: carrying inventory may not be a bad idea after all!

Inventory management pedagogy, practice and research have shifted dramatically since the second decade of the past century from EOQ to JIT, from mass production to mass customization, from long to short product life cycles, etc. This shift was due to the markets becoming dynamic, global and competitive resulting in faster and increasing consumption by customers. The continuous increase in customers' demand resulted in products moving faster along a supply chain (SC) and generating more waste that had a severe environmental impact; CO_2 emission, landfill, etc. Societies, especially in Europe, are becoming more conscientious about the environment with legislation that holds manufacturers responsible for their products beyond their life-cycles. This has resulted in introducing new business terms such as recycling, refurbishing, reuse and remanufacturing; synonymous with reverse logistics (RL).

Concepts or terms such as JIT, SCM, RL, etc., were developed in an 'economic era' that assumed fossil fuel to be an efficient and abundant main energy resource. These assumptions may not hold in a few years time. Fossil fuel reserves are declining, and it is unlikely that there will be an economically viable energy replacement in the near future. Perhaps even more important is that the use of fossil fuels adds to the amount of CO_2 emissions. Therefore, for economic and for environmental reasons, we may have to rethink how robust our inventory management concepts are in the light of deepening energy crisis (the cost of a barrel of crude oil increased from about $25 in 2002 to $140 in 2008).

Contemporary inventory management systems that use smaller batch sizes, shorter product life cycles, reverse logistics, etc., significantly increase transportation costs, CO_2 emissions, waste from disposed packaging material, scrap, etc. Perhaps, the inventory management paradigm for the coming years should be to move towards larger batch sizes, longer product life cycles (reduce obsolescence cost), higher quality items (reduce deterioration cost), and thus may decrease the unit holding cost. Perhaps the continued increase in energy prices may result in deglobalisation of markets, if not decentralization. For example, Torontonians may no longer be able to afford to import tomatoes in winter (sub zero temperature) from Mexico or California when the price of fuel per litre is $2. Toronto (and the province of Ontario) must consider innovative agricultural solutions to grow tomatoes in harsh winter conditions. In other words, a move towards smaller self-sustainable markets would be a strategic solution to consider.

The following is a simplistic model that extends the EOQ model to include some environmental costs. We refer to this model as the environmental Economic order quantity (Enviro-EOQ) model.

Notation

mu monetary units (e.g., $, £, €)
A order cost (mu)
c unit purchase cost (mu/unit)
h holding cost (mu/unit/year)
a fixed cost per trip (mu)
b variable cost per unit transported per distance travelled (mu/unit/km)
d distance travelled (from supplier to buyer, km)
α proportion of demand returned ($0<\alpha<1$)
D demand rate (units/year)
β social cost from vehicle emission (mu/h)
v average velocity (km/h)
γ cost to dispose waste to the environment (mu/unit)
θ proportion of waste produced per lot Q.

A.1. Mathematical modelling

EOQ cost per cycle:

$$C(Q)=A+cQ+h\frac{Q^2}{2D} \tag{A.1}$$

Transportation cost per cycle (delivery and collection of returned items):

$$C_t(Q)=2a+bdQ+bd\alpha D\frac{Q}{D}=2a+bdQ+bd\alpha Q \tag{A.2}$$

Emission cost from transportation per cycle:

$$C_e(Q)=2\beta\frac{d}{v} \tag{A.3}$$

The number '2' refers to a roundtrip. If Q is delivered to the buyer in several shipments, then the values of d and a should be adjusted to reflect the additional costs incurred.

Waste produced by the inventory system per cycle:

$$C_w(Q)=\gamma_0+\gamma Q(\theta+\alpha) \tag{A.4}$$

where γ_0 is the fixed cost per waste disposal activity.

The total cost per unit of time is $\psi(Q)=[C(Q)+C_t(Q)+C_e(Q)+C_w(Q)]/T$, where $T=Q/D$ is the cycle time. Then,

$$\psi(Q)=\frac{AD}{Q}+cD+h\frac{Q}{2}+\frac{2aD}{Q}+bdD+(1+\alpha)+2\beta\frac{dD}{vQ} + \frac{\gamma_0 D}{Q}+\gamma(\theta+\alpha)D \tag{A.5}$$

The optimal solution is given as

$$Q=\sqrt{\frac{2D}{h}\left(A+2\alpha+2\beta\frac{d}{v}+\gamma_0\right)} \tag{A.6}$$

Note that h could also be modelled to adjust to an increase or decrease in energy prices. This may make the mathematics slightly more complex. Taking the ratio of the Enviro-EOQ to the classical EOQ, where the latter is given as $Q_0=\sqrt{2AD/h}$, to get

$$\frac{Q}{Q_0}=\sqrt{1+\frac{2a+2\beta(d/v)+\gamma_0}{A}} \tag{A.7}$$

From (A.7), one can deduce that the optimal ordering policy when environmental costs are used is to order in larger lot sizes than the EOQ.

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