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Integrated business continuity and disaster recovery planning: Towards organizational resiliency

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Abstract

Businesses are increasingly subject to disruptions. It is almost impossible to predict their nature, time and extent. Therefore, organizations need a proactive approach equipped with a decision support framework to protect themselves against the outcomes of disruptive events. In this paper, a novel framework is proposed for Integrated Business Continuity and Disaster Recovery Planning for efficient and effective resuming and recovering of critical operations after being disrupted. The proposed model addresses decision problems at all strategic, tactical and operational levels. At the strategic level, the context of the organization is first explored and the main features of the organizational resiliency are recognized. Then, a new multi-objective mixed integer linear programming model is formulated to allocate internal and external resources to both resuming and recovery plans simultaneously. The model aims to control the loss of resiliency by maximizing recovery point and minimizing recovery time objectives. Finally, at the operational level, hypothetical disruptive events are examined to evaluate the applicability of the plans. We also develop a novel interactive augmented ε-constraint method to find the final preferred compromise solution. The proposed model and solution method are finally validated through a real case study.

Research highlights:

- Proposing a new conceptual framework for IBCDRP;
- Formulating a novel resource allocation model for IBCDRP framework;
- Developing a novel interactive augmented ε-constraint method;
- Validating the proposed model and solution technique via a real case study.

Keywords: *Risk management, Organizational resiliency, Disaster operations management, Business continuity planning, Disaster recovery planning, Multi-objective mixed integer programming*.

1. Introduction

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Organizations are increasingly facing with various types of disruptions that could take place individually or simultaneously. Each disruption might have different effects on organizational resources. Traditionally, Business Continuity Planning (BCP) and Disaster Recovery Planning (DRP) as the main contingency plans are carried out separately in different time horizons within organizations (Wunnava, 2011). BCP aims to develop appropriate plans at pre-disaster in order to resume key business operations to a minimum acceptable predefined level (i.e., Minimum Business Continuity Objective (MBCO)) immediately after a disruptive event within the so-called Maximum Tolerable Period of Disruption (MTPD) through invoking appropriate BC plan(s). On the other hand, DRP strives to ensure the full recovery (restoration) of all disrupted operations to their normal business state at post-disaster (ISO:22310, 2012). The concept of *organizational resiliency* is attracting growing attention among academicians and practitioners. In short, it enquires organizations to develop effective plans for both short-term resuming (i.e., BC plans) and long-term restoration (i.e., DR plans) of their disrupted operations following disruptive events (Riolli and Savicki, 2003). Being prepared for disruptive events requires proactive planning of internal and external resources of the organization so that it can cope with disasters effectively and efficiently. However, lack of proactive BC and DR planning may lead to loss of reputation and market share, customer service and business process failure, regulatory liability and increased resuming and restoring times (Herbane, et al., 2004; Hiles, 2010; Losada, et al., 2012). There might be several alternate BC and/or DR plans for the same disruptive event (for example hot sites versus cold sites) each of which has its own resource requirements and utilization rates. Nevertheless, by taking into account different limitations such as available budget and shared resources, such contingency plans should be implemented in an integrated manner. Without such integral planning, managers wouldn't have known when and how to switch from continuity phase to recovery phase, while making a trade-off between continuity and recovery plans, and arranging resources after happening disruptive incidents. To the best of our knowledge, it is the first time in the literature that an integrated BC and DR planning model is proposed.

In this paper, a novel Integrated Business Continuity and Disaster Recovery Planning (IBCDRP) framework is developed. Subsequently, an interactive Multi-Objective Mixed Integer Linear Programming (MOMILP) model is formulated to find efficient (i.e., Pareto-optimal) resource allocation patterns among candidate BC and DR plans while considering the main features of the organizational resiliency. To solve the proposed model, a novel Interactive AUGmented ε-CONstraint method (named IAUGCON) is developed. Finally, the proposed IBCDRP model is validated through application to a real case study in a manufacturing company. The main contributions of this paper can be outlined as follows:

- Proposing a new conceptual framework for IBCDRP.
- Formulating a novel MOMILP model to address the resource allocation problem within the IBCDRP framework while accounting for the main features of the organizational resiliency.
- Developing a novel interactive augmented ε-constraint method to find compromise solutions.
- Validating the proposed model and solution technique through application in a real case study.

2. Literature review

The literature of disaster management dates back to the 1980s. It is intertwined in a multi-disciplinary research area bringing together academics and practitioners from several disciplines such as public administration and organizational crisis management. Unfortunately, DRP for businesses still lacks a methodological direction (Altay and Green, 2006). For years, many organizations have ignored the significance of disaster management and continuity planning (Herbane, 2010). Based on reports, 43% of companies influenced by severe disasters never reopened, and about 30% of them failed within two years (Cerullo and Cerullo, 2004). Such statistics emphasize the need for proactive approach by organizations equipped with a decision support framework to effectively protect their processes against disruptions and reduce their negative impacts.

According to the disaster management's life-cycle, two main phases are commonly distinguished as *pre-disaster phase* and *post-disaster phase* (Tufekci and Wallace, 1998). In pre-disaster phase, emergency managers have moved their focus beyond the immediate response and short-term recovery and are now re-focusing their efforts more on the continuity of organizations. In this phase, professionals are placing greater emphasis on the resiliency of organizations (Labadie, 2008). Organizational resiliency is concerned with the development of suitable BC plans to resume disrupted Critical Operations (COs) of an organization to their minimum acceptable operating levels as quickly and efficiently as possible and DR plans to restore all disrupted operations to their normal operating levels following any disruptive event (Losada, et al., 2012). Many scholars argue that recovery is not only a process with short term resumption, but also long-term restoration to get back to initial state of disrupted processes/operations (Olshansky and Chang, 2009). In this manner, we propose a novel IBCDRP model that involves introducing a management process dedicated to selection and implementation of the most appropriate business continuity (i.e., resuming) and recovery (i.e., restoring) plans.

There is a limited literature on developing decision models for business continuity and recovery planning. These include some research works such as recovery of computer networks (Ambs, et al., 2000), and selection of disaster recovery alternatives for organizational crisis management (Bryson et al., 2002). Despite of little work on developing integrated BCP/DRP models for organizational crisis management, many researchers have addressed immediate response and recovery planning for society/urban areas mostly in response to natural disasters in the context of Humanitarian Logistics (HL) and Disaster Operations Management (DOM) (Das and Hanaoka, 2014; Edrissi, et al., 2013; Eiselt and Marianov, 2012; Preece, et al., 2013; Wex, et al., 2013). For more details on HL models and DOM from the Operational Research/ Management Science (OR/MS) point of view, the interested readers may refer to Altay and Green (2006) and Galindo and Batta (2013).

While the field of integrated BC and DR planning has attracted the interests of information technology scholars for a number of years, OR/MS research in this area is so limited. Albores and Shaw (2008) argued that OR/MS research plays an essential role in the improvement of decision models for emergency activities in post-disaster phase. Furthermore, as indicated by Altay and Green (2006), just 6.4% of surveyed papers were related to OR/MS outlets in recovery phase. Recently, Galindo and Batta (2013) emphasized that there has been no extreme growth for application of OR/MS methodologies /tools in the field of DOM since the review of Altay and Green (2006).

Based on above discussion, we were able to conclude that the main focus of researchers has ever been on developing the general features of an integrated BC and DR planning framework rather than devising decision support models. Decision making about how to resume and restore critical operations of an organization at post-disaster phase is inherently complex. Organizations may lose some of their resources partially or completely after disruptive events (Jackson, 1997). Consequently, there will be a natural discrepancy between plans and real situations most of the times. An effective integrated BC and DR planning framework should rely on a systematic assessment of all features of each possible incident. Furthermore, such planning decisions are usually restricted by limited and changeable resources, organizational complexities, and the need to search effective plans for resumption and restoration of organizational critical operations (Snediker, et al., 2008).

To alleviate the complexity and difficulty of DOM, Bryson et al. (2002) presented a mathematical model by using of formal OR/MS techniques. They believed that the proposed model could guarantee effectiveness of the selected plans when put into operation. However, their model did not account for the continuity of the organization's operations at early post-disaster phase. Losada et al. (2012) presented a bi-level mixed integer linear program for protecting an incapacitated median type facility by considering system resiliency. However, they focused on the problem of reducing the impact of component failures on service and supply systems. According to Altay and Green (2006), ensuring the continuity of critical operations at pre-defined levels in post-disaster is a critical issue for any organization. More recently, as a continuation of earlier review of DOM by Altay and Green (2006), Galindo and Batta (2013) reviewed recent OR/MS research in DOM and concluded that most of the research gaps highlighted by Altay and Green (2006) have been remained without any drastic changes. Following the research directions and gaps identified by Bryson et al. (2002), Altay and Green (2006) and Galindo and Batta (2013), we address a comprehensive resource allocation problem faced by organizations who try to protect themselves against various business disruptions through integrating the BC and DR plans into an novel IBCDRP framework.

3. The proposed IBCDRP framework

We first present the theoretical foundation of the proposed IBCDRP framework from different perspectives and then go through the developed IBCDRP model addressing the resource allocation problem when selecting the best portfolio of BC and DR plans simultaneously.

3.1 Theoretical foundation

The conceptual framework of our IBCDRP model is illustrated in Figure 1 which is based upon the concept of operational resiliency. Figure 1.a shows an organization equipped with an IBCDRP model and figure 1.b depicts an organization with a stand-alone DRP model. When a disruptive event strikes at time t_1, it may lead to disruption of some critical operations. Consequently, the current operating level of a disrupted critical operation is reduced from l_1 to l_2. The respective recovery plan is expected to start at time t_2, and go on until t_3, when it is completely restored (i.e. operating level reaches to l_1). Let $\varpi(t)$ denotes the resumed level of the critical operation as a function of elapsed time. The loss of resilience in the organization can be obtained by the amount of reduced operating level (l_1-l_2) and required time to recovery (t_3-t_2). For the first time, Bruneau et al., (2003) introduced a mathematical expression for the loss of resilience as $LR = \int_{t2}^{t3} [l_1 - \varpi(t)]dt$

Noteworthy, although calculation of operational resiliency is emphasized by scholars, the lack of quantitative approaches to measure the operational resiliency of an organization can be perceived (Erol, et al., 2010). Based on the resiliency definition provided by Bruneau et al., (2003), two main measures should be considered including the restoration period and the reduction amount (loss) of operating level. While in the DRP, only the restoration period can be controlled, in IBCDRP model both of these resiliency measures are controllable. Accordingly, an approximation for *LR* is equal to the coloured area as shown in figure 1.a and 1.b. However, it should be noted that distinct combinations of restoration time and the reduction amount of operating level may have the same *LR* (Zobel and Khansa, 2014). For example, as shown in figure 1.a, a set of plans that lead to significant reduction in operating level (l_2) but has shorter restoration time (t'_3) may have the same *LR* as another set of plans that have less reduction in operating level (l''_2) but a longer restoration time (t_3).

There are two main points in the proposed IBCDRP framework that includes: overlapping of business continuity and recovery plans and resource allocation. As shown in figure 1.a, there is an overlap between BC and DR plans in the IBCDRP framework so that BCP starts at the occurrence of disruptive event (t_1) while the DRP starts after finishing of initial effects of disruptive event (t_2). The key challenge of this paper is deciding on how to allocate available resources among candidate continuity and recovery plans such that the *LR* is minimized. In fact, the amount of allocated resources to each plan, directly affects both of resiliency measures (i.e., the loss of operating level and restoration time). As such, the developed IBCDRP framework should be able to make and validate an integrated continuity and recovery plan for the organization's critical operations not only before, but also during and after any disruptive event by arranging required resources in advance. Here, a novel mathematical model is formulated to tackle the resource allocation problem faced within the IBCDRP framework which accounts for operational resiliency features and both internal and external resources jointly.

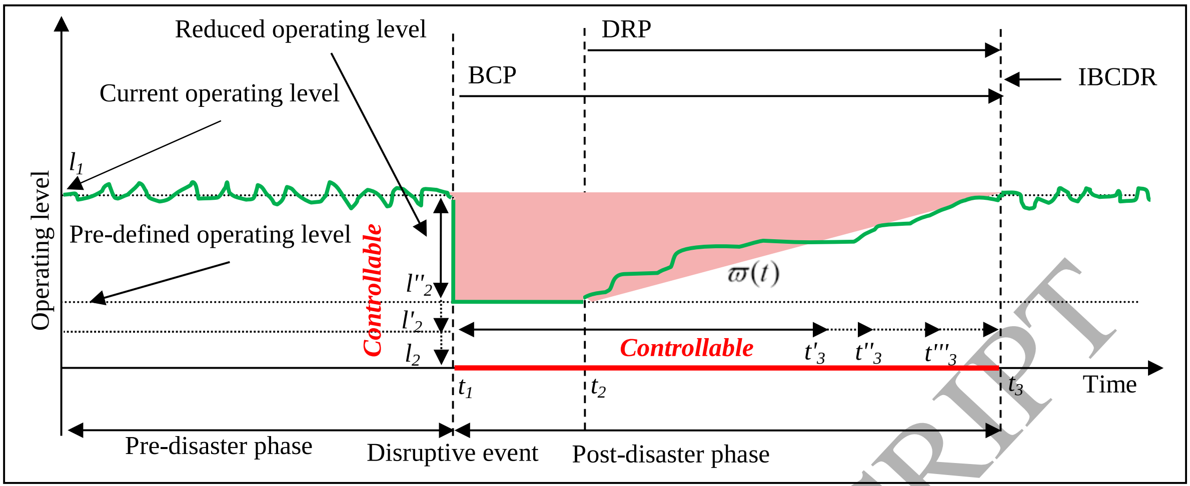

Figure 1.a. An IBCDRP model based on the resiliency triangle

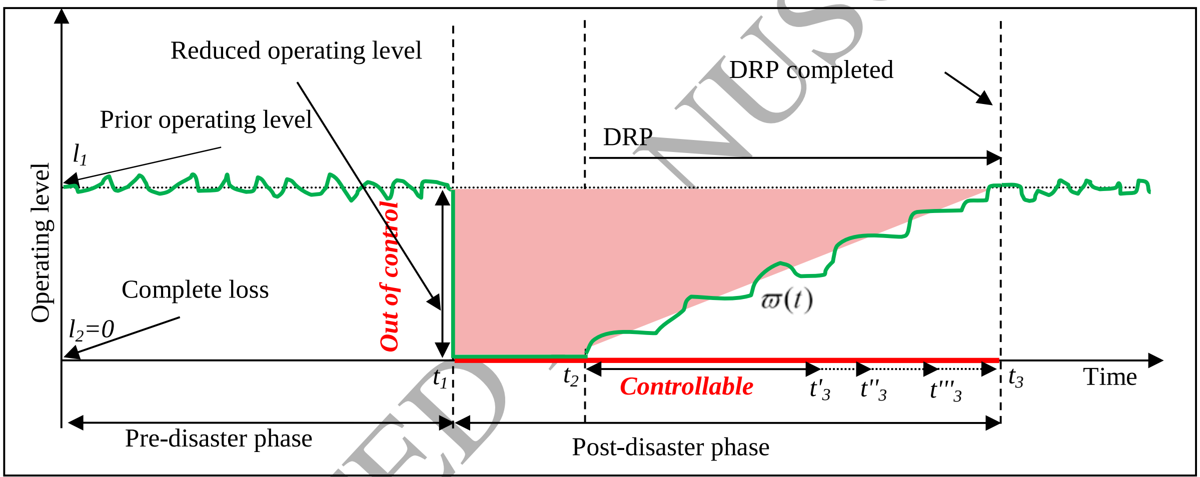

Figure 1.b. A DRP model based on the resiliency triangle

3.2 Details of the IBCDRP framework

In the simple terms, IBCDR is a proactive framework to concurrently generate continuity and recovery plans in pre-disaster phase to deal with disruptive events at post-disaster efficiently and effectively. In this way, IBCDRP framework could be considered as a main part of Business Continuity Management System (BCMS) which enables meeting the continuity and recovery objectives of the organization in different levels of tolerable losses (Liu, et al., 2009). A comprehensive IBCDRP should involve the three decision levels: strategic, tactical and operational ones as shown in Figure 2.

At the strategic level, via investigating both internal and external environments of the business, causes and likelihoods of the possible disruptive events, IBCDRP goals and BCMS scope can be determined. These elements of the IBCDRP fall in the pre-disaster phase as the initial step of developing the IBCDRP model within an organization in terms of time scale. Then, by determining the critical operations, and identifying the internal and external resources of the organization, the IBCDRP framework enters to the next decision level (the interested readers can consult with Sharp, 2008 for determining BCMS requirements in detail). At the tactical level, continuity and recovery plans are created as tactical decisions. Each disruptive event will decrease the operational capacity of whole organization by reducing the availability level of some of organization's resources. In this situation, remained resources must be allocated to resume/restore those disrupted critical operations in order to guarantee the business continuity and recovery goals through selecting a sub-set of candidate plans in response to various disruptive events in the most efficient and effective way. Consequently, a new mathematical formulation for resource allocation problem is proposed to develop appropriate continuity and recovery plans simultaneously. The optimal resource allocation not only ensures resuming and restoring of disrupted operations, but also makes a trade-off between continuity and recovery plans. Notably, there is no similar IBCDRP resource allocation model in the literature so far. Since such a decision (i.e. generating contingency plans to response disruptive events) might be changed in accordance to strategic plan of the organization, we have known it as a tactical decision. The IBCDRP should control the losses of operating levels and recovery times simultaneously. Admittedly, this might not happen without preparing the organization in pre-disaster phase. In this way, the first two decision levels could be made in pre-disaster phase. However, selected BC and DR plans are worthless unless they are rehearsed (Sharp, 2008). Therefore, having generated the BC/DR plans, they must be tested and evaluated at the operational level. To do so, hypothetical disruptive events that could simulate real disruptive events' circumstances will help to evaluate the effectiveness of the selected plans. If the proposed plans satisfy continuity measures (i.e., MBCO and MTPD), then they will be validated; otherwise, they should be modified at tactical level. Noteworthy, the IBCDRP framework might test the plans more than once in pre-disaster phase based on various hypothetical disruptive events. In this way, incorporating an evaluating procedure in the IBCDRP framework can guarantee that deviations within the plans are fixed before they are used in reality.

4. Resource allocation model formulation

Consider an organization whose critical operations, i.e., the required sub-processes for delivering the key services/products along with their required resources are given. Let S is the set of key services/products and P denotes the set of respective COs. A pair of CO and its respective key product is represented by the combination (*sp*). Each CO requires a specific amount of resource type j to be continued at operating level l indexed by $R^{l}_{(sp)j}$. Indeed, a lower operating level of each CO needs fewer amounts of resources than its higher operating levels. When a disruptive event happens, a particular set of circumstances are changed and several causes can affect different resources. This situation could lead to a disruption and loss of operating level. Each disruptive event d, is characterized by three parameters including the likelihood of occurrence (β^{d}), its impact on internal resource j at time t (κ^{dt}_{j}) and on external resource j (η^{d}_{j}).

According to International Organization for Standardization (ISO) terminology in regards to BCMS (ISO:22310, 2012), we define MTPD for each key product as the time it would take for undesirable impacts, which might arise as a result of not providing products or performing an operations, to become unacceptable (γ_{s}). Also, the MBCO is defined as the minimum operating level of each key product that is acceptable to the organization to achieve its business objectives (e.g., preserving reputation/brand, reducing financial losses and continuous serving of products) during a disruption (λ_{s}).

According to the proposed IBCDRP conceptual framework, the recovery time objective (RTO) as the actual selected resumption time according to the allocated resources, should be less than or equal to MTPD, while the recovery point objective (RPO) as the actual selected resumption level according to the allocated resources, should be more than or equal to MBCO. To reach an integrated BC/DR planning, decision-makers must consider a number of options to effectively allocate the available resources for continuity and recovery purposes of the organization. We present a new multi-objective mixed integer linear programming (MOMILP) model which helps the decision makers to allocate resources among competing BC and DR candidate plans to optimize robustness and rapidity of the organization's reactions to disruptive events. The proposed MOMILP model aims to increase the RPO (i.e., resumption level) in the BC phase of the proposed IBCDRP and subsequent planned operating levels in the DR phase in accordance to resource limitations along with minimizing the total recovery time. To this end, the RPO and RTO restrictions are considered as two constraints and minimizing the total recovery time and subtraction of planned operating levels from highest operation levels are considered as the two objective functions.

4.1 Assumptions

The main characteristics and assumptions used for formulation of the resource allocation problem are as follows:

- The organization has two main status including the normal and disrupted situations;
- Several disruptive events can occur simultaneously;
- The organization has several key products whose delivery requires a number of COs;
- Each CO has its own relative importance that represents the priority of that CO for restoring and resuming.
- Each disruptive event has its own disruptive effects and may disrupt required resources of some COs partially or completely;
- There are different operating levels for performing each CO (e.g., normal, 70% normal, etc.) whose required resource utilization rates are known;
- The business continuity measures, i.e., the MBCO and MTPD for each key product and their corresponding COs are given based on the organization's business impact analysis. Furthermore, the RPO and RTO of each key product are determined by solving the resource allocation model whereby the associated MBCO and MTPD are acting as their lower and upper bounds, respectively;

- In a normal condition, the operating level of each CO is assumed to be at its maximum value (i.e., 100% of available capacity);
- After a disruption, a fraction of internal and external resources are available for resuming and restoring of disrupted COs;
- External resources are the same as internal resources. Hence, the lost internal resources are replaced by external resources of the same types in a disruptive situation;
- In a disrupted condition, average unit cost for each utilized external resource is given;
- Restoration of each disrupted CO requires allocation of some pre-determined resources;
- A disruptive event reduces the amount of both internal and external resources simultaneously;
- A multi-period horizon is available to resume and restore disrupted COs. Furthermore, the length of the planning horizon is at least equal to maximum MTPD among key products.

Indices:

d Index of disruptive events ($d=1,2,\dots,D$)
s Index of key services/products ($s=1,2,\dots,S$)
l Index of operating levels ($l=1,2,\dots,L$)
p Index of critical operations ($p=1,2,\dots,P$)
j Index of resources ($j=1,2,\dots,J$)
t Index of time ($t=1,2,\dots,T$)

Parameters:

γ_s The MTPD for key product *s*
λ_s The MBCO for key product *s*
(sp) The pair of key product *s* and critical operation *p*
ξ_j^E The amount of available external resource type *j* in the normal condition
$R_{(sp)j}^l$ The amount of required resource type *j* for pair (*sp*) at level *l*
C_j^E Average unit cost of external resource *j* in a disrupted condition
β^d Likelihood of disruptive event *d*
κ_j^{dt} The impact of disruptive event *d* on internal resource *j* at time *t*
η_j^d The impact of disruptive event *d* on external resource *j*
ω_s Relative importance of the key product/service *s*
B_t Available budget at time *t* under disastrous condition

Variables:

$x_{(sp)}^{lt}$ 1, if the operating level of pair (sp) at time t is equal to l, 0, otherwise

R_j^{Et} The amount of required external resource j consumed for IBCDRP at time t

R_j^{It} The amount of required internal resource j consumed for IBCDRP at time t

ϖ_s^t The planned operating level of key product s at time t

ϑ_s The recovery time of key product s

4.2. Problem formulation

The proposed MOMILP model for dealing with the resource allocation problem within the proposed IBCDRP framework is as follows:

$$Min\ f_1 = \sum_{s=1}^{S}\sum_{t=1}^{T}\omega_s.(L - \varpi_s^t) \tag{1}$$

$$Min\ f_2 = \sum_{s=1}^{S}\omega_s\vartheta_s \tag{2}$$

s.t. $$\sum_{l=1}^{L} x_{(sp)}^{lt} = 1 \qquad \forall (sp),t \tag{3}$$

$$\sum_{l=1}^{L} l.x_{(sp)}^{lt} \geq \lambda_s \qquad \forall (sp),t \geq \gamma_s \tag{4}$$

$$\sum_{l=1}^{L} l.x_{(sp)}^{lt} - \sum_{l=1}^{L} l.x_{(sp)}^{l(t-1)} \geq 0 \qquad \forall (sp),t \geq 2 \tag{5}$$

$$\sum_{s=1}^{S}\sum_{p=1}^{P}\sum_{l=1}^{L} R_{(sp)j}^{l}.x_{(sp)}^{lt} \leq R_j^{Et} + R_j^{It} \qquad \forall j,t \tag{6}$$

$$\sum_{s=1}^{S}\sum_{p=1}^{P} x_{(sp)}^{l1}.R_{(sp)j}^{l} \leq \sum_{s=1}^{S}\sum_{p=1}^{P} R_{(sp)j}^{L} - \sum_{d=1}^{D}\beta^d.\kappa_j^{d1} \qquad \forall j,l \tag{7}$$

$$\sum_{s=1}^{S}\sum_{p=1}^{P} R_{(sp)j}^{L} - \sum_{d=1}^{D}\beta^d.\kappa_j^{dt} \geq R_j^{It} \qquad \forall j,t \tag{8}$$

$$\xi_j^E - (\frac{1}{t})^t \sum_{d=1}^{D}\beta^d.\eta_j^d \geq R_j^{Et} \qquad \forall j,t \tag{9}$$

$$\sum_{j=1}^{J} R_j^{Et}.C_j^E \leq B_t \qquad \forall t \tag{10}$$

$$\sum_{l=1}^{L} l.x_{(sp)}^{lt} \geq \varpi_s^t \qquad \forall (sp),t \tag{11}$$

$$(T - \sum_{t=1}^{T} x_{(sp)}^{Lt} + 1) \leq \vartheta_s \qquad \forall (sp) \tag{12}$$

$$\vartheta_s \leq \gamma_s \qquad \forall s \tag{13}$$

$$x_{(sp)}^{lt} \in \{0,1\} \qquad \forall (sp),l,t \tag{14}$$

$$\varpi_s^t, R_j^{Et}, R_j^{It}, \vartheta_s \geq 0 \qquad \forall s,j,t \tag{15}$$

Objective function (1) minimizes the weighted sum of key products' loss of resilience during the IBCDRP time horizon. Objective function (2) minimizes the weighted sum of recovery times following an incident within which all key products are completely restored. These two objective functions can help DMs for achieving greater robustness and rapidity measures, respectively according to the selected BC/DR plans.

Constraints (3) warrant that just one operating level to be assigned to each pair of (*sp*) at any given time. Constraints (4) ensure that the operating level of each pair of (*sp*) is greater than respective MBCO after MTPD. Constraints (5) guarantee that the operating level of each pair of (*sp*) is not decreased during the IBCDRP horizon. Constraints (6) make sure that the amounts of required resources are less than accessible internal and external resources in each time period. Notably, the levels of organization's resources are decreased following any disruptive event. So, operating level of each pair of *(sp)* will be reduced according to the loss level of resources. Constraints (7) guarantee that the required resources for the active operating level of each pair of (*sp*) at the first time period do not exceed the available resources while accounting for the expected value of capacity losses affected by possible disruptive events. As shown in Figure 1.a, when a disruptive event strikes, it will lead to disruption of some critical operations. We propose this constraint to control the operating level of critical operations at pre-defined levels. Since the impact of disruptive events on resources would be reduced along the successive periods of IBCDRP horizon, constraints (8) ensure that required internal resources do not exceed the expected remained amount of internal resources in each time. Similarly, constraints (9) assure that the required external resources following disruptive events do not exceed the expected remained amount of external resources in each time. Noteworthy, the amount of external resources will be increased along the successive periods of IBCDRP horizon. Constraints (10) set the budget limitation for provision of external resources in each time. It is noteworthy that to keep the continuity of the organization's critical operations in disruptive situations, using external resources of same types when there is no enough internal resources; could be supportive while the amount of borrowed/hired external resources depends on the budget limitation of the organization. Constraints (11) determine the operating level of the key products in each time. Constraints (12) specify the RTO of each key product. Constraints (13) guarantee that the RTO of each key product should not exceed its respective MTPD. Finally, Constraints (14) and (15) enforce the binary and non-negativity restrictions on corresponding decision variables. The resulting model is a MILP model with $S(T+1)+2J\times T$ continuous variables and $(S\times P\times L\times T)$ binary variables. The number of constraints is also $(SP(4T-S-1)+T(3J+1)+JL+S)$, excluding constraints (14) and (15).

5. The proposed solution methodology

To solve the MOMILP problem, we should find a final preferred compromise solution belonging to the Pareto set (see Ehrgott, (2005) for definitions on weakly efficient and efficient solutions in MOPs). The MOP methods are classified into three categories: the priori, the interactive and the posterior (also called generating) methods (Xidonas et al., 2011). The ε-constraint method is one of the most popular approaches among generating methods in which the Pareto set is estimated by changing the epsilon vector of constrained objectives and solving their corresponding Single-Objective Programs (SOP) (Rastegar and Khorram; Zhang and Reimann, 2014). Various versions of the ε-constraint method have been developed in the literature, trying to improve its original presentation or adjust it to a particular form of problem (Engau and Wiecek, 2007). Let's start with a MOP involving *z* objective functions $f_i(x), i = 1,...,z$, subject to $x \in X$, where *x* is the vector of decision variables and *X* denotes the feasible decision space. Without loss of generality, we assume that all objective functions are of maximization type. In the ε-constraint method, we optimize a SOP as follows (Xidonas, et al., 2011):

$$Max\ \{f_1(x) \mid x \in X \wedge f_i(x) \geq \varepsilon_i, i = 2,...,z\} \tag{16}$$

To generate different ε-vectors, the range of each constrained objective function is first determined by constructing the so called pay-off table. Afterwards, it is divided into a number of intervals based on some grid points. In this way, solving the respective single-objective model for each ε-vector (which consists of one grid point of each constrained objective); results in a Pareto-optimal (i.e., an efficient) solution for the MOP. Finally, the decision maker can select the most preferred efficient solution out of these obtained Pareto-optimal solutions based on her/his preferences (Engau and Wiecek, 2007). According to Mavrotas (2009), one disadvantage of the ordinary ε-constraint method is that there is no guarantee for efficiency of the generated solutions. To overcome this shortcoming, Mavrotas (2009) formulated an augmented version of the ε-constraint method (see Mavrotas, 2009). Another disadvantage of the current ε-constraint based methods is their huge required computation time. To overcome these deficiencies, we develop a new interactive ε-constraint based method that not only guarantees the efficiency of the obtained solutions but also decreases the required computation time considerably by developing a novel aggregation function. This method does not abandon any of the potential solution and is capable to deal with medium- to large-sized MOPs. The proposed IAUGCON method includes three steps which are elaborated hereafter.

Step1: Calculate the upper bounds $(f_i^{ub}, i = 1,...,z)$ and lower bounds $(f_i^{lb}, i = 1,...,z)$ for the constrained objective functions $i = 2,...,z$.

Finding appropriate f_i^{lb} and f_i^{ub} at least for *(z-1)* constrained objective functions that will be used as constraints is the basis of ε-constraint method (Mavrotas, 2009). These points give an indication for the range of objective values which non-dominated points can achieve. While f_i^{ub} values are obtained by solving (*z-1)* single objective optimization problems easily, computation of f_i^{lb} values is a very difficult task (Ehrgott, 2005). Due to the difficulty of computing f_i^{lb}, the iterative *Algorithm 1* is proposed in which a single objective problem (i.e., $\max\ \{f_i(x) \mid x \in X, \forall i = 1,...,z\}$) is first solved iteratively. Let x_i^* and f_i^* denote the solution vector and optimal solution of the i^{th} single objective model (i.e., the upper bound of respective objective function) respectively. Adding this optimal solution as a new constraint enforces optimizing other objective functions separately.

Algorithm 1:
i=1
While $i \le z$
$f_i^* = \max\ \{f_i(x) \mid x \in X\}$
j=1
for *j=1* to *z* and $j \ne i$
$f_j(\hat{x}_{ji}) = \max\{f_j(x) \mid f_i(x) = f_i^* \wedge x \in X\}$
i=i+1
end while.
$f_i^{ub} = f_i(x_i'), i = 1...z$
$f_i^{lb} = \max_{i=1,...,z, i \ne j} f_j(\hat{x}_{ji}), j = 1...z$

Proposition 1. *Algorithm 1* sets proper upper and lower bounds for the set of non-dominated solutions in the IAUGCON method to avoid from generation of weakly efficient solutions.

Proof. To prove the *proposition 1* we need to assure that there is no $x \in X$ such that *f(x)* dominates f_i^{ub} and weakly dominates f_i^{lb}.

First, assume that there is one $x \in X$ such that *f(x)* dominates $f(x')$. This means that $f_i(x) \ge f_i(x_i')$ and at least for one objective function $f_i(x) > f_i(x_i')$. But this contradicts the initial assumption that $f_i(x_i') = \max\{f_i(x) \mid x \in X\}, \forall i = 1...z$. Simply, there is no $x \in X$ such that its objective function is strictly greater than $f_i(x_i')$. Second, assume that f_i^{lb} be a weakly non-dominated solution. This means that there exist $x'' \in X$ such that at least one objective function is greater than

f_i^{lb}. But this contradicts the initial assumption that the lower bounds of objective functions are set as the maximum value of $f_j(\hat{x}_{ji}) = \max\{f_j(x) \mid f_i = f_i(x_i') \wedge x \in X\}$. Moreover the optimal solutions of the constrained problems in the second step are efficient (Ehrgott, 2005). By searching among all generated single objective problems ($z \times (z-1)$) and choosing the maximum value of objective functions, we avoids from weakly efficient solutions.

Step 2: Generate the initial epsilon vectors. In this step, the range of each constrained objective function must be divided into a number of intervals by some grid points. Then, Mavrotas (2009) technique is used to generate various epsilon vectors.

Step 3: Apply the interactive IAUGCON algorithm to generate different efficient solutions. We propose the novel augmented model (P) to find the efficient solution interactively to remove the deficiencies of the previous ε-constraint based methods.

$$\text{Model(P)}: Max\ \ w_1^k . f_1^k(x) + (\varepsilon_1^{k+1} - \varepsilon_1^k) \times \delta . (\sum_{i=2}^{z} w_i^k . (\bar{\varepsilon}_i^{k+1} - \varepsilon_i^k) / (\varepsilon_i^{k+1} - \varepsilon_i^k) - M . \sum_{i=2}^{z} s_i^k \ / (\varepsilon_i^{q_l} - \varepsilon_i^k))$$

$$\begin{aligned} s.t.\ \ & f_i^k - s_i^k = \bar{\varepsilon}_i^k && \forall i = 2,\dots,z \\ & s_i^k \geq 0 && \forall i = 2,\dots,z \\ & \bar{\varepsilon}_i^k \geq \varepsilon_i^k && \forall i = 2,\dots,z \\ & \bar{\varepsilon}_i^k < \varepsilon_i^{k+1} && \forall i = 2,\dots,z \\ & x \in X \end{aligned} \qquad (17)$$

Generally, in an interactive approach, the preferences of the DM are progressively fed into the solution process (Sun, 2005). In this way, w_i^k denotes the weight of i^{th} objective function for the k^{th} epsilon vector and is determined by the decision maker based on her/his preferences. Furthermore, ε_i^k and ε_i^{k+1} are the k^{th} and $(k+1)^{th}$ grid points of the i^{th} objective function and δ and M are a small and a big number, respectively. The first and second terms of the proposed augmented objective function ensure yielding an adjustably balanced compromise solution for each cut of epsilon vector. The third term of the proposed augmented objective function tries to fit the constrained objective functions on the best epsilon value in the range that is formed by the third and fourth constraints. Moreover, it controls the satisfaction level of objectives as well as the decision maker preferences among the objectives implicitly. On the other hand, to solve model (P), the preferences of the DM are progressively gained for each range of epsilon. The second term of the augmented objective function, tries to improve the value of each constrained objective function according to the DM's preferences in different ranges.

Proposition 2. The proposed model (P) only produces efficient solutions.

Proof. Assume that the model P (for one range of epsilon, *k=1*) has an alternative optima (say $\hat{x}$) which dominates the optimal solution x'. This means that:

$$(f_1', \overline{\varepsilon}_2' + s_2' + ... + \overline{\varepsilon}_z' + s_z') \leq (\hat{f}_1, \hat{\overline{\varepsilon}}_2 + \hat{s}_2 + ... + \hat{\overline{\varepsilon}}_z + \hat{s}_z) \quad (18)$$

Note that f_1' and $\hat{f}_1$ are same for both x' and $\hat{x}$ because we assume that model P have alternative optima and $f_1' = \hat{f}_1 = \max f_1(x)$. Since $(f_1', \overline{\varepsilon}_2' + s_2' + ... + \overline{\varepsilon}_Z' + s_Z')$ is dominated by $(\hat{f}_1, \hat{\overline{\varepsilon}}_2 + \hat{s}_2 + ... + \hat{\overline{\varepsilon}}_Z + \hat{s}_Z)$, there is at least one strict inequality in (18). By taking the sum of these relations we conclude that:

$$\sum_{z=2}^{Z} (\hat{\overline{\varepsilon}}_z + \hat{s}_z) > \sum_{z=2}^{Z} (\overline{\varepsilon}_z' + s_z') \quad (19)$$

But this contradicts the initial assumption that the optimal solution of model P (i.e. x') maximizes the sum of $\overline{\varepsilon}_z'$ and s_z'. Hence, the obtained solution x' from model (P) is efficient. □

In this way, model (P) only generates efficient solutions based on the DM's preferences in different ranges of epsilon vectors. At the same time, it reduces the required computation time considerably by taking off infeasible epsilon direction in the nested loops. The IAUGCON algorithm generates different efficient solutions. The DM's decisions and obtained solutions in various iterations will guide the search towards the most preferred Pareto optimal solution after a number of iterations. Two issues including acceleration of the algorithm and diversity of the solutions have been considered when developing the IAUGCON algorithm. For acceleration, the algorithm will exit from the nested loops of epsilon values when the problem becomes infeasible in one direction. However, the algorithm starts from the f_i^{lb} and gradually restricts the bounds to f_i^{ub}. When model (P) in the IAUGCON algorithm becomes infeasible, there is no need to further restrict the corresponding objective function. So, the algorithm exits from the loop and proceeds with the next grid point of the previous objective function that corresponds to the outer loop. IAUGCON algorithm is shown in figure 3 schematically. In addition, we avoid the generation of the same solutions by replacing new lower and upper bounds instead of epsilon value in IAUGCON Algorithm. L_i^k and U_i^k are the respective lower and upper bound of RHS in each iteration. These values are obtained by adding the slack s_i^k to the epsilon value. So the obtained solution will be different. Now, with a graphical example we show how the IAUGCON algorithm works.

IAUGCON Algorithm

For i=1 to z

$L_i^1 = \varepsilon_i^1$

$U_i^1 = \varepsilon_i^2$

i=i+1

K=1

For i=2 to *z*

⊗ Solve Model (P)

$$\left(\begin{array}{l} P1: \max\ \mathrm{w}_1.f_1^k(x) + (U_1^k - L_1^k)\times\delta.(\sum_{i>1, i\le z} w_i.(\overline{\varepsilon}_i^k - L_i^k)/(U_i^k - L_i^k) - \\ \qquad M.(\sum_{i>1, i\le z} s_i^k/(f_i^{ub} - L_i^k))) \\ s.t. \\ f_i^k - s_i^k = \overline{\varepsilon}_i^k \wedge \overline{\varepsilon}_i^k \ge L_i^k \wedge \overline{\varepsilon}_i^k < U_i^k \wedge x \in X \end{array} \right)$$

If Model (P) is feasible

then

$ES^k = \vec{x}$ (ES^k denotes the set of efficient solutions)

$L_i^k = \min\left\{\overline{\varepsilon}_i^k + s_i^k, U_i^k\right\}$

$U_i^k = \max\left\{\varepsilon_i^{k+2}, U_i^k + s_i^k\right\}$

K=k+1

Go to ⊗

else

$L_i^k = L_i^1$

$U_i^k = U_i^1$

i=i+1

Figure 3. IAUGCON algorithm

Assume a problem with three objective functions whose objective space is shown in figure 4. First, we start with the more relaxed version of the constrained objective functions i.e. $L_i^1 = \varepsilon_i^1 = f_i^{lb}$. Then, the bound of the third objective function is gradually restricted until arriving to point A. By solving model (P) with constrained objective functions $L_2^3 = \varepsilon_2^1$ and $L_3^3 = \varepsilon_3^3$ the amount of slack s_3^3 is more than $\varepsilon_3^4 - \varepsilon_3^3$. In fact, the solution obtained from model (P) with constrained objective functions $L_2^4 = \varepsilon_2^1$ and $L_3^4 = \varepsilon_3^4$ would be equal to the preceding solution. Hence, we jump to point (B) from point (A). Since model (P) in point (B) is feasible and slack value is zero, then we go to the next point (C). At this point, model (P) becomes infeasible. Therefore, the algorithm exits from the innermost loop and proceeds with the next grid point (D).

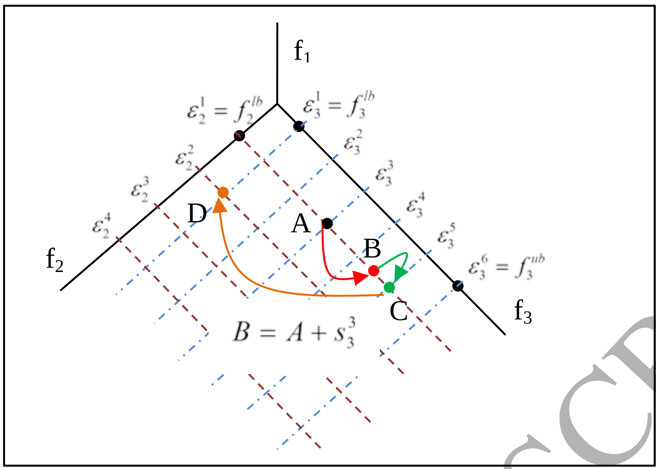

Figure 4. The graphical representation of algorithm 3

6. Case study

In this section, we describe our case study and the data collection procedure which is used to evaluate the proposed IBCDRP model and its solution approach.

6.1 Outline of the case study

The case study was conducted for a Gear Box Company in the north of Iran to show how to deal with possible disruptions. The company is a small and medium enterprise (SME) that produces different types of Gear Box (GB). There are different operations for manufacturing of GBs in three shops including casting, machining and assembly shops. According to the proposed IBCDRP framework (as shown in figure 2), identifying the company's goals and interested parties, the goals and scope of the IBCDRP were emphasized at this stage. Notably, several meeting with different personnel of the company at different levels were necessary for data gathering. Getting the full agreement and commitment of the board of directors during the data gathering phase was the main struggle. However, the main goals of the organization were explored by reviewing the current strategic plan of the organization. The company's goals include: increase in customer satisfaction, increase in market share up to 30% for product type S and up to 22% for product type M and improvement of the supply chain service. To identify the major interested parties of the company, we first divided them into three categories. The first category included shareholders, customers, clients, personnel, and suppliers who are so close to the company while regulators, investors, insurance companies, competitors, and government are part of the second category. The media groups and interested NGOs were considered as the third category of the interested parties. Then, they were ranked based on their expectations and impacts on the organization. Consequently, the major interested parties of the company were identified as customers, personnel and shareholders. Subsequently, the scope of IBCDRP that determines the issues to be covered by the IBCDRP was drawn by considering factors such as major goals and interested parties, size, complexity, environment, location, and activity types of the company. The machining centre was identified as the initial scope of the IBCDRP. By exploring the major goals and interested parties of the GB Company and identifying the scope of IBCDRP, the goal of IBCDRP was determined. Keeping the operating levels of the product types S and M at 80% under any circumstances was also set as the main goal of IBCDRP. Determining the key products and their critical operations was the next stage which was done through Business Impact Analysis (BIA) proposed by Sikdar (2011) and Torabi et al. (2014). In this manner, two product items from each product type were chosen as the key products. Finally, the critical operations of these key products were recognized according to their process routes and criticality criteria such as technological level, capability of insuring, recovery time and cost. Information regarding the key products and their critical operations along with their MTPD and MBCO measures has been summarized in Table 1. Furthermore, Analytic Hierarchy Process (AHP) was applied to calculate the relative importance of critical operations and reported in Table 1.

Table 1. Key-products and critical operations

Key product	γ_s (days)	λ_s (operating level)	ω_s	Critical operations (*sp* pairs)
GB06-S10	4	6	0.263	Casting (11), Drilling(12), Hobbing (13), Assembling (14)
GB06-M10	3	4	0.421	Casting (21), Shaving (22), Hobbing (23), Assembling (24)
GB12-S15	5	5	0.106	Casting (31), Machining (32), Milling (33), Assembling (34)
GB12-M15	4	6	0.21	Casting (41), Machining (42), Cutting (43), Assembling (44)

To complete the required data to run the proposed IBCDRP at the strategic level, the possible disruptive events and required internal and external resources for their recovery should be recognized. In this regard, four types of resources were considered, i.e., facilities (i.e., physical buildings), equipment (i.e., machines and tools), manpower and power (energy). Also, ten operating levels were set for each critical operation from 1 to 10. Operating level 1 means that the critical operation is halted (i.e. no resources are available), while operating level 10 means that the critical operation continues with its maximum (100%) capacity and company is in a normal condition (i.e. all resources are available). For example, based on the production plan in the normal situation, drilling process should produce 50 units per hour (at its operating level 10). However, if a disruptive event occurs and the output of drilling process is to be reduced to 40 units per hour, its operating level is considered as 8.

Table 2. The amount of needed resources for each product at each level

Critical operation (CO)	Resources																			
	Facilities										Equipment									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
(11)	0	80	80	100	100	150	150	150	150	200	0	4	4	4	4	7	7	9	9	9
(12)	0	8	8	8	8	16	16	16	16	16	0	1	1	1	1	2	2	2	2	2
(13)	0	7	7	7	7	14	14	14	14	14	0	1	1	1	1	2	2	2	2	2
(14)	0	20	20	30	30	30	30	40	40	40	0	5	5	5	5	5	5	5	5	5
(21)	0	80	80	100	100	150	150	150	150	200	0	4	4	4	4	7	7	9	9	9
(22)	0	3	3	3	3	5	5	5	5	5	0	1	1	1	1	2	2	2	2	2
(23)	0	7	7	7	7	14	14	14	14	14	0	1	1	1	1	2	2	2	2	2
(24)	0	20	20	30	30	30	30	40	40	40	0	5	5	5	5	5	5	5	5	5
(31)	0	80	80	100	100	150	150	150	150	200	0	4	4	4	4	7	7	9	9	9
(32)	0	6	6	14	14	14	21	21	21	21	0	1	1	2	2	2	3	3	3	3
(33)	0	8	8	8	8	8	8	8	8	8	0	1	1	1	1	1	1	1	1	1
(34)	0	20	20	30	30	30	30	40	40	40	0	5	5	5	5	5	5	5	5	5
(41)	0	80	80	100	100	150	150	150	150	200	0	4	4	4	4	7	7	9	9	9
(42)	0	6	6	14	14	14	21	21	21	21	0	1	1	2	2	2	3	3	3	3
(43)	0	6	6	14	14	14	21	21	21	21	0	1	1	2	2	2	3	3	3	3
(44)	0	20	20	30	30	30	30	40	40	40	0	5	5	5	5	5	5	5	5	5
Total	[IR=1100,ER=200]										[IR=80,ER=10]									
Cost	[CI=10000,CE=200000]										[CI=70000, CE=500000]									

Table 2. Continue

Critical operation (CO)																				
	Manpower										Power									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
(11)	0	7	9	9	9	9	15	15	15	15	0	4	7	10	18	20	23	25	28	30
(12)	0	2	2	2	2	4	4	4	4	4	0	1	1	1	1	2	2	2	2	2
(13)	0	2	2	2	2	4	4	4	4	4	0	2	2	2	2	3	3	3	3	3
(14)	0	6	6	9	9	9	9	12	12	12	0	1	1	1	1	1	1	1	1	1
(21)	0	7	9	9	9	9	15	15	15	15	0	4	7	10	18	20	23	25	28	30
(22)	0	1	1	1	1	2	2	2	2	2	0	1	1	1	1	2	2	2	2	2
(23)	0	2	2	2	2	4	4	4	4	4	0	2	2	2	2	3	3	3	3	3
(24)	0	6	6	9	9	9	9	12	12	12	0	1	1	1	1	1	1	1	1	1
(31)	0	7	9	9	9	9	15	15	15	15	0	4	7	10	18	20	23	25	28	30
(32)	0	2	2	3	3	3	4	4	4	4	0	1	1	3	3	3	5	5	5	5
(33)	0	2	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2
(34)	0	6	6	9	9	9	9	12	12	12	0	1	1	1	1	1	1	1	1	1

(41)	0	7	9	9	9	9	15	15	15	15	0	4	7	10	18	20	23	25	28	30
(42)	0	2	2	3	3	3	4	4	4	4	0	1	1	3	3	3	5	5	5	5
(43)	0	2	2	3	3	3	4	4	4	4	0	1	1	3	3	3	5	5	5	5
(44)	0	6	6	9	9	9	9	12	12	12	0	1	1	1	1	1	1	1	1	1
Total	[IR=136,ER=54]										[IR=200,ER=14]									
Cost	[CI=20000, CE=40000]										[CI=10000, CE=20000]									

After determining different types of required resources and operating levels, the amount of needed resources for critical operations at defined levels (i.e., resource consumption rates) were determined by well-known Material Requirements Planning (MRP) technique according to the current Bill of Materials (BOMs) in the Company. The MRP indicates what and how many resources are needed to run each operation. For example, drilling operation needed 16, 2, 4, and 2 units of facility, equipment, manpower, and power respectively in its normal condition. The amount of available internal and external resources, unit cost of resources and the amount of needed resources for critical operations at different levels were normalized and summarized in Table 2. Finally, according to the geographical position, climate condition and current reports and documents about happened disruptive events within the company, five distinctive types of disruptive events consisting of flood, earthquake, fire, personnel sabotage and epidemic diseases were taken into account. After gathering the aforementioned data, the initial stage of developing IBCDRP model in the pre-disaster phase was completed.

At the second stage of IBCDRP model's development (i.e. planning); tactical decisions should be made. For this, three scenarios including the optimistic, realistic and pessimistic ones have been generated to tackle the unpredictable situations of the company in the future. For each scenario, the likelihood and impact of respective disruptive event on both internal and external resources were set according to the available documents in the department of risk management within the organization about the happened disruptive events during the last 3 years (see Table 3).

6.2 Results

The main results of the proposed approach are presented below. For solving the resulting resource allocation model of the GB Company, the proposed MOMILP algorithm has been solved by CPLEX 10.

According to step 1 of the proposed solution method, the upper and lower bound of objective functions (i.e., loss of resilience and resuming time) are obtained by applying *Algorithm 1* for each scenario whose results have been reported in Table 4. Then, the initial epsilon vectors are generated according to the second step of the proposed solution method. Here, we divided the range of objective functions by five grid points into equal intervals which have been summarized in Table 4. In the third step, the model (P) of IAUGCON algorithm has been formulated for resource allocation model as follows:

$$\text{Model(P)}: Min\ \text{w}_1.f_1^{\,k}(x) + (\varepsilon_1^{k+1} - \varepsilon_1^{k}) \times \delta.(w_2.(\bar{\varepsilon}_2^{k+1} - \varepsilon_2^{k}) / (\varepsilon_2^{k+1} - \varepsilon_2^{k}) + M.(s_2^{k} / (\varepsilon_2^{q_l} - \varepsilon_2^{k}))$$

s.t.

$$\sum_{s=1}^{S} \omega_s^k \vartheta_s^k - s_2^k = \bar{\varepsilon}_2^k;\ \ s_2^k \geq 0;\ \ \bar{\varepsilon}_2^k \geq \varepsilon_2^k;\ \ \bar{\varepsilon}_2^k < \varepsilon_2^{k+1}$$

\+ Equations (3)-(11)

In the last step, IAUGCON algorithm is used to generate different efficient solutions. We asked the board of directors to suggest their preferences for different ranges of resiliency loss and resuming time interchangeably.

Table 3. The likelihood and impact of disruptive events on internal and external resources

Scenarios	Disruptive event	β^d	Impact on Resources (κ_j^{d1}, η_j^d)			
			Facilities	Equipment	Manpower	Power
Realistic	Earthquake	U[0.1,0.2]	(715,130)	(52,7)	(88,10)	(130,9)
	Flood	U[0.3,0.5]	(220,40)	(16,2)	(27,3)	(40,3)
	Fire	U[0.35,0.55]	(440,0)	(32,0)	(54,0)	(80,0)
	Personnel sabotage	U[0.25,0.4]	(132,0)	(56,0)	(95,0)	(26,0)
	Epidemic diseases	U[0.5,0.7]	(0,0)	(0,0)	(40,5)	(0,0)
Optimistic	Earthquake	U[0.04,0.06]	(550,100)	(40,5)	(68,8)	(100,7)
	Flood	U[0.24,0.36]	(385,70)	(28,4)	(47,6)	(70,5)
	Fire	U[0.21,0.41]	(605,0)	(44,0)	(74,0)	(110,0)
	Personnel sabotage	U[0.14,0.26]	(165,0)	(64,0)	(108,0)	(48,0)
	Epidemic diseases	U[0.35,0.56]	(0,0)	(0,0)	(84,8)	(0,0)
Pessimistic	Earthquake	U[0.18,0.34]	(880,160)	(64,8)	(108,12)	(160,11)
	Flood	U[0.48,0.64]	(495,90)	(36,5)	(61,7)	(90,6)
	Fire	U[0.54,0.69]	(770,0)	(56,0)	(95,0)	(140,0)
	Personnel sabotage	U[0.48,0.54]	(253,0)	(72,0)	(122,0)	(62,0)
	Epidemic diseases	U[0.75,0.84]	(0,0)	(0,0)	(119,9)	(0,0)

Table 4. Upper and lower bounds of objective functions and initial epsilon vectors

Scenario	upper bound		Lower bound		epsilon values of f_2				
	f1	*f2*	*f1*	*f2*	ε_2^1	ε_2^2	ε_2^3	ε_2^4	ε_2^5
Optimistic	5.235	8.648	4.41	2.321	16	12.580	9.161	5.741	2.321
Realistic	8.495	12.84	4.811	2.427	16	12.686	9.266	5.847	2.427
Pessimistic	18.59	18.059	11.756	2.848	16	13.107	9.687	6.267	2.848

The obtained results for each scenario were summarized in Table 5 and represented graphically for product GB06-S10 in Figure 5. Due to space limitation, the related graphical representations were provided in Figures 1 to 3 of the Supplementary material for other products. Subsequently, we determined a specific range for each resource that guarantees the continuity of critical operations at predefined levels. Internal facility and equipment usage charts and the range of them are shown in Figure 6. Internal manpower and electricity usage charts and range of resources at each time are shown in Figure 5 of Supplementary material. For example, to satisfy the MTPD and MBCO of the company, our plans have been drawn such that provide [659,831], [827,930], [928,990], and [989.1026] units (m^2) of facilities during 4 days after disruption, respectively. For the external resources, the company's continuity plans consists of 4 separate contracts for each resource. Sub-contractors assure to provide [28,69], 4, [19,52], and [4,8] units of facilities, equipment, manpower, and power, respectively.

Table 5. Calculated RTO and operating levels of products based on the three scenarios

Scenario	products	RTO	Operating levels														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Optimistic	GB06-S10	2	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	GB06-M10	1	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	GB12-S15	2	5	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	GB12-M15	9	1	3	7	7	7	7	7	7	10	10	10	10	10	10	10
Realistic	GB06-S10	4	3	8	9	10	10	10	10	10	10	10	10	10	10	10	10
	GB06-M10	1	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	GB12-S15	8	1	1	1	3	6	6	7	10	10	10	10	10	10	10	10
	GB12-M15	14	2	3	4	4	7	7	7	7	7	7	7	7	9	10	10
Pessimistic	GB06-S10	4	1	5	7	10	10	10	10	10	10	10	10	10	10	10	10
	GB06-M10	1	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	GB12-S15	8	1	1	1	1	5	5	5	10	10	10	10	10	10	10	10
	GB12-M15	13	1	3	5	6	6	6	6	6	7	7	7	8	10	10	10

6.2.1 Evaluation of results

In order to evaluate the effectiveness of the plans, we propose three indices including: the average loss of resilience (ALR), RTO and the total loss (TL). Subsequently, an evaluation was carried out by simulating a hypothetical disruptive event in the organization.

We calculated the resumption level (i.e., RPO) and real operating levels of each disrupted CO over the planning horizon according to the impact of simulated disruptive event and shown in Figure 7. As shown in this figure, the obtained RTO and RPO through a hypothetical disruptive event validate the proposed plan. Furthermore, according to the mathematical formulation of loss of resilience, the amount of ALR, RTO and TL have been measured for each product and summarized in Table 6. ALR, RTO and TL are fallen into the acceptable ranges for all products except GB12-M15. Since this product has the least relative importance, the board of directors decided to allocate fewer resources to it compared to other products. This issue will be released by promoting the resiliency level of the organization through the next years. Consequently, we recommended to the board of directors to sub-contract some of the operations to release resources which are needed to keep the operating levels of the whole critical operations at their predefined levels. Due to the budget restriction, the board of directors decided to implement the IBCDRP plan under the optimistic scenario for the first year and promote the resiliency level of the GB Company during the next three years. In this manner, managers of the organization could evaluate the BC/DR plans and the resiliency level of their organization more than once based upon the different strategic and tactical decisions made in the pre-disaster phase. Indeed, the IBCDRP can reveal the interactions between strategic and tactical decisions and resiliency level of the organization that is usually one of main concerns of the company's managers.

Table 6. Obtained average loss of resilience, resumed time and total amount of loss

	Scenarios									Hypothetical disruptive event		
	Optimistic			Realistic			Pessimistic					
products	ALR	RTO	TL	ALR	RTO	TL	ALR	RTO	TL	ALR	RTO	TL
GB06-S10	0.5	2	0.5	2.5	4	6.5	4.25	4	12.5	3.5	2	4.5
GB06-M10	0	1	0	0	1	0	0	1	0	0	1	0
GB12-S15	2.5	2	2.5	5.6	8	40.5	6.375	8	46.5	6.71	7	58
GB12-M15	3.8	9	29.5	3.7	14	48.5	4	13	53	3.92	13	46.5

The results of the case study indicate that the proposed solution method for solving the resulting MOMILP model is an appropriate approach which can produce different efficient solutions based on the decision maker's preferences in a reasonable time. This approach can also be used for solving other practical MOP models. The results of this research indicate that the proposed IBCDRP framework is very promising for providing organizational resiliency subject to operational limitations. It also demonstrates the usefulness and capability of OR/MS approaches for decision making in the area of DOM.

7. Concluding remarks

In this article, we proposed an integrated business continuity and disaster recovery planning framework that includes all strategic, tactical and operational decision levels with different timeframes, and various elements of the IBCDRP at each level. In addition, the proposed framework consists of a novel resource allocation mathematical model to determine the required resources to cope with disruptive events. IBCDRP creates required BC/DR plans to ensure that the organizations can respond to disruptive events in the most efficient and effective way by providing an appropriate level of organizational resiliency. In other words, developing an integrated contingency plan to get ready the organization to cope with disruptive events ensures the organization to be able to resume and restore the critical operations of the organization in disruptive situations as quickly and effectively as possible with minimal resources and budget. To show the capability and usefulness of the proposed framework, a real case study was examined in a gear box manufacturer. Results demonstrate that the proposed IBCDRP framework is an applicable methodology to manage the continuity and recovery plans in an organization.

Future research could explore the concept of business continuity for building resilient organizations by considering simultaneous or consecutive multiple disruptive incidents. Furthermore, proposing more quantitative measures of resiliency can lead to better illustration of usefulness and capability of MS/OR tools in this area. In addition, taking the inherent uncertainty in the model's parameters into account and using of uncertainty programming techniques such as fuzzy/possibilistic programming, robust programming, and mixed fuzzy stochastic programming is another avenue for further research.

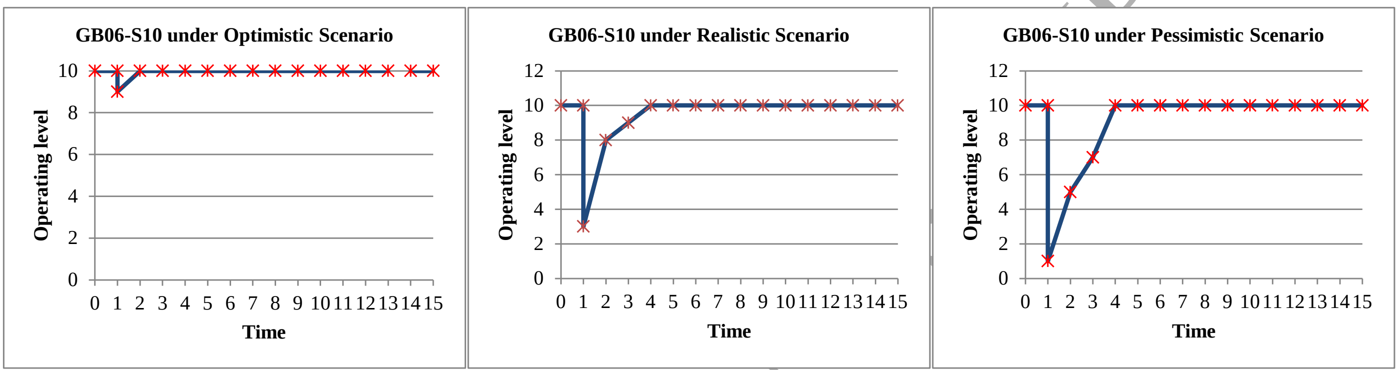

Figure 5. Obtained resiliency triangles for GB06-S10 under three scenarios

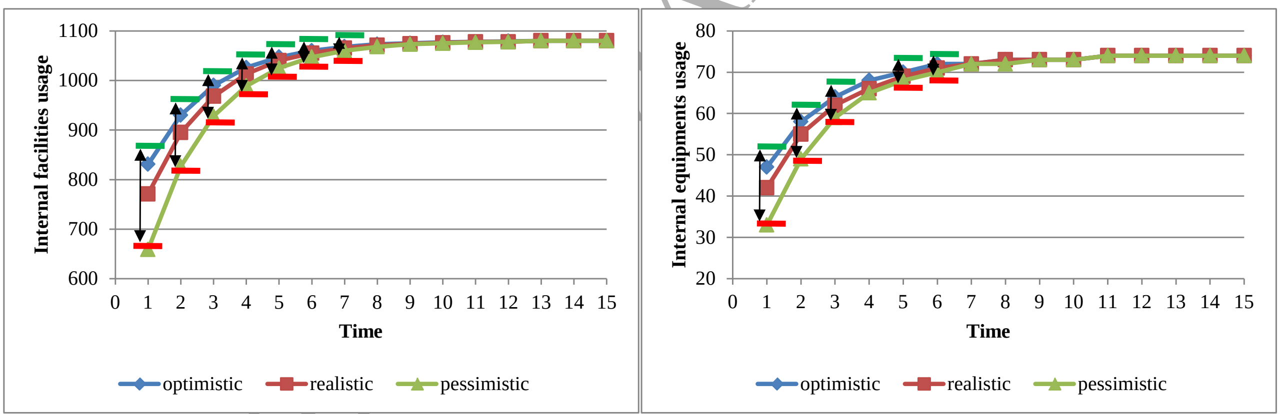

Figure 6. Internal facility and equipment usage charts and range of resources at each time

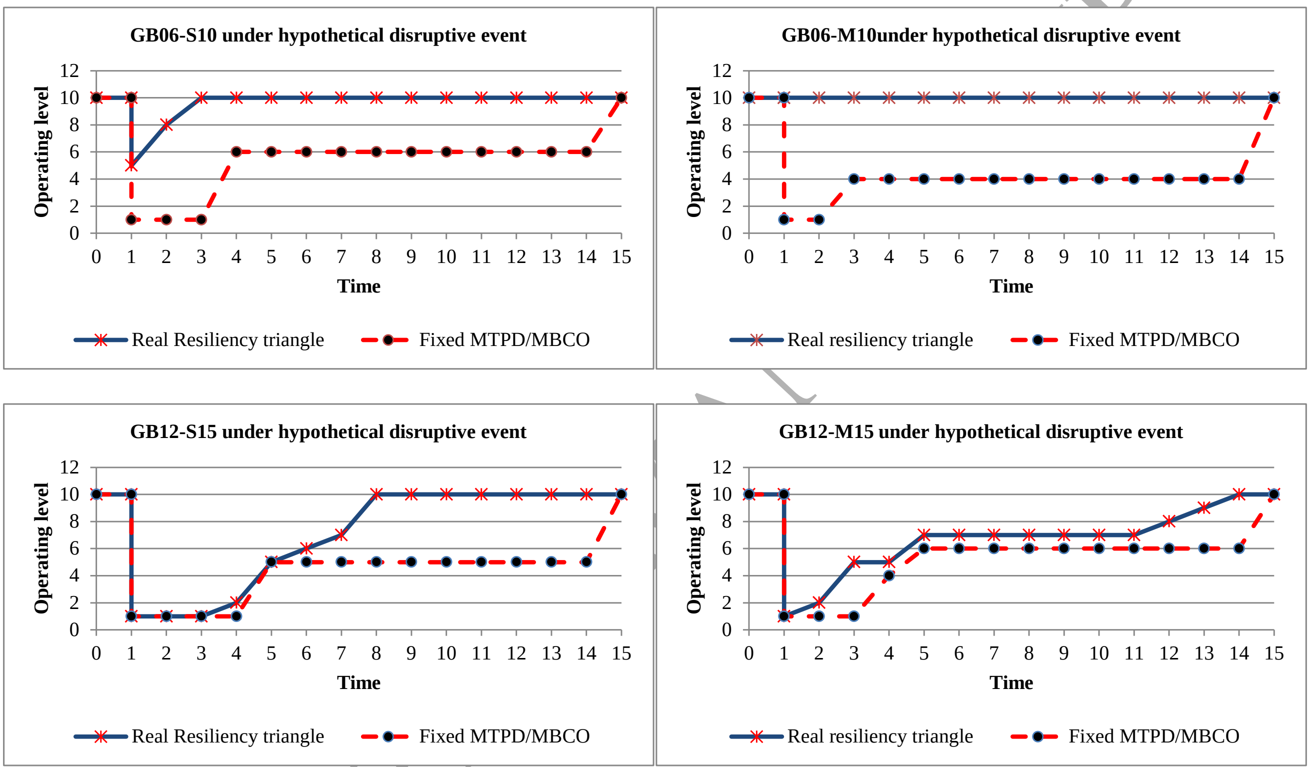

Figure 7. Resource usage charts and range of resources at each time

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