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Developing and Assessing Alternative Land-Use Scenarios from the MOLAND Model: A Scenario-Based Impact Analysis Approach for the Evaluation of Rapid Rail Provisions and Urban Development in the Greater Dublin Region

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Abstract: In this study, environmental sustainability implications of planned rail infrastructure investments on the urban form and development in the Greater Dublin Region (GDR) have been analysed incorporating the scenario analysis approach. Various scenarios are developed using the MOLAND Model applications including: A baseline scenario incorporating a continuation of the present dispersed pattern of urban development and an alternative scenario with rail-oriented corridor development, under varying conditions of economic growth. An alternative scenario was also developed for the recessionary development case considering the prolonged recession in the GDR. Further explorations incorporating a Cost-Benefit Analysis (CBA) approach are developed to evaluate the sustainability implications of different land development scenarios in the Dublin Region. This is assisted by focussing on the impacts of rail investments on urban form and development as raised in the international comparative literature. The findings from the CBA assessment positively indicate that containment policies-as represented by the public transport oriented development indicate benefits over the dispersed development case by reducing the negative consequences of sprawl type of developments. In contrast, dispersed development in the baseline scenario indicates costs of continuation of such development patterns exceed the benefits in the long term. This study will contribute to policy support evaluation measures relating to the integration of scenario analysis tool with the CBA approach in assisting the evaluation of new transport infrastructure proposals.

Keywords: urban development patterns; scenario analysis; MOLAND Model; rail infrastructure investment; Greater Dublin Region; cost-benefit analysis

1. Introduction

In recent decades, rapid growth of peri-urban areas in many of the European metropolitan centres has resulted in significant consequences on the development of the urban environment. Most of the cities have experienced dispersed or scattered type of development often referred to as 'urban sprawl' in contrast to their more compact structures observed until the 1950s [1]. Transformation from compact to more dispersed structures has significant implications on the urban environment:

negative effects on the air and water quality, increased travel and accessibility costs and unwanted social equity costs are often cited as some of the most important problems faced by many metropolitan centres [2,3]. The existence of such problems has led to a focus on the policies of urban sustainable development and urban growth management within the context of sustainability. In this respect, the main concern in research over recent decades is the search for the linkages between urban spatial structure and transportation systems which will achieve sustainable urban form and efficient transport provisions [4,5]. Efficiency of transportation is closely related to the evolving urban structure since the degree of compactness and density affect commuting distance and time, feasibility of the main transport system and travel-related energy consumption and pollution levels.

In relation to differing sustainability implications resulting from various land-use-transport policies, scenario development has become a common tool among scholars, practitioners and policy makers for the impact assessment of various policies on the transportation system and associated land-use changes [6–8]. In practical applications, scenario analysis is achieved using computer-based land-use modelling, which provides the basis to simulate alternative land development patterns ranging from urban containment to sprawl or transport-oriented corridor developments [7,9]. Recently, simulation models have become more sophisticated in dealing with individuals and their behaviour. Some, such as agent-based systems, deal explicitly with agents like people and cars, while others, especially Cellular Automata (CA) [10,11], deal with plots of land that can take on various uses [12–14]. This latter category is especially important in urban and regional applications as it allows the modelling of land-use dynamics at a very high resolution. The MOLAND (Monitoring Land-Use/Cover Dynamics) Model used in this study is a CA-based model and can be considered as one of the most potentially inclusive models due to its wide application in research and policy analysis both in EU and outside European countries [7,15]. The MOLAND is a state-of-the-art land-use model developed by the Research Institute for Knowledge Systems (RIKS) for the Joint Research Centre (JRC) of the European Commission (EC) to provide technical and scientific support concerning the implementation of EU policies. The purpose of the model is monitoring, assessing and modelling the development of urban and regional environments across European member states [16]. It has been applied to an extensive network of cities and regions, with an approximate total coverage of 70,000 km^2 in Europe [17] and has recently been used in for individual region case studies [18–20].

The focus of this research is to develop and evaluate land-use-transport sustainability implications of various land development scenarios for the Greater Dublin Region (GDR). The Dublin Region was considered as an example of one of the worst cases of sprawl type development in research conducted by EEA [1]. It is recognised that dispersed or sprawl patterns have significant implications for the long-term regional development patterns as in the case of Dublin. In this context, the MOLAND Model was calibrated for the GDR [21] as part of the Urban Environment Project (UEP) (UEP was carried out at University College Dublin in the School of Geography, Planning and Environmental Policy/Urban Institute Ireland and funded by the Environment Protection Agency) in line with the Dublin and Mid-East Regional Authority's aim to provide Strategic Environment Assessment for the GDR. This calibrated model has been used to assist in evaluating the impacts of different policies and programmes on urban development considering the sustainability in urban form and transport-land-use relationships.

There are increasing numbers of studies focusing on the land-use modelling approach for the ex-ante sustainability impact assessment of different forms of urban development. For instance, extensive literature exists on relations between land-use patterns and environmental impacts, e.g., soil degradation [22], water supply [23], biomass energy [24] and urban sprawl [25]. Other research focus on analysing the changes of land-use patterns through integrating socio-economic and policy related changes into a set of simulation models [26] or examine the environmental impacts of urban land-use transitions in a conceptual framework [27]. This body of literature consists of studies focusing on sustainability impact assessment of land-use and transport strategies. There are studies on the development of performance indicators, accessibility measures or socio-economic and environmental impact analysis [28–30]. However, there are limited contexts where wider sustainability impacts (economic, social and environmental) of transportation-land-use relationship are examined through integration of land development scenarios into the impact evaluation framework [31–33]. Therefore, this paper contributes to the literature by providing an integrated approach to transport and land-use policy making in longer term-incorporating scenario analysis and cost-benefit assessment methodologies- to help assess a range of alternative policy options.

The paper outlines and evaluates the results of MOLAND modelling work based on three different land-use scenarios developed for the GDR based on various transportation and associated development trends and policy implications. A Cost-Benefit Analysis (CBA) approach is utilised in this research for the evaluation of socio-economic and environmental impacts of new rail transport infrastructure provision and policy changes on land development processes. This is carried out through the selection of relevant impacts and indicators, used for assessing costs and benefits in terms of their contribution to social welfare.

The second section provides a literature review for the development and assessment of land-use scenarios within the context of sustainability implications of the transportation-land-use relationships. In relation to this, the third section explains the methodology for the scenario analysis and the evaluation of the transportation and land-use relationship in the GDR. In section four, the results from the scenario analysis and the CBA are presented and discussed, which is followed by conclusions.

2. Methodologies for the Development and Assessment of the Land-Use Scenarios

2.1. The Land-Use Modelling Framework

The EC [17] recognised the importance of the links between land-use choices and their potential impacts and noted that the quantification of these impacts is crucial for the development of sustainable policies (see also EEA [34]). Therefore, 'simulations of land-use changes and their potential consequences can provide necessary information for the preparation, development and assessment of major spatial plans and strategies' (EC [17], p. 5). There are various research projects launched by the EC (e.g., under the sixth framework programme) focusing on the links between land-use changes and their potential impacts and some of them are aiming at developing modelling tools for supporting policy decisions [17]. There are three principal sets of models identified by the EC ([17], p. 45): (1) sectorial models (e.g., CAPRI, EFISCEN) estimating regional demands and restrictions for land-use change for different sectors (2) global models (e.g., IMAGE, NEMESIS) providing information on products and world market prices (3) land-use allocation models (e.g., METRONAMICA, CLUE-s) specifying potential land-use changes for the future considering the demands from different sectors, suitability, attractiveness and spatial policies.

There is no single modelling approach proven superior to others for predicting future land-use changes; and the choice of a specific model depends on the purpose and policy implications of the study as well as on data availability [35]. Land-use models usually aim to allocate land-use changes based on selected driving forces, competition between different land-uses and the use of spatial allocation rules. There are various land-use modelling approaches and their diversity can be explained by 'wide range of research questions in which models are utilised as tools and the different scales of application, ranging from the very local to the global extent' (EC [17], p. 49). The details on different modelling tools and applications can be seen in EC [17].

2.2. Evaluation Methodologies for Assessing Land-Use-Transport Impacts on Urban Development

The relationship between sustainability of the urban form and transportation efficiency constructed a base for the studies evaluating the economic aspects of various urban forms which will provide efficient transport systems. The literature that is related to the land-use-transport interactions can be examined under two main groups. The first group focuses on specific indicators to measure and evaluate costs and benefits of transportation provisions to assess the sustainability relationships between transportation and land-use development. Considerable research has been performed on the accessibility impacts of transportation provisions including Martinez and Araya [36]; Geurs and Van Wee [28]; and Willigers et al. [37]. This literature incorporates scenario analysis into the accessibility appraisal of integrated transport-land-use strategies. This is developed through deriving accessibility measures and examinations of the transport-land-use relationship incorporating these accessibility measures on different land development scenarios. Geurs et al. [38] dealt with accessibility impact evaluation of different land-use scenarios by introducing comprehensive accessibility measures in their integrated transport-land-use model for their study area of Netherlands. The study by Kwok and Yeh [39] is another example for integrated transport-land-use scenario analysis. Their contribution to previous work is to introduce the modal accessibility gap index which is related to the difference between accessibility indices of public and private transportation. This constructed a base for further studies aiming at analysing the issue of land development in the context of transportation sustainability.

The second group analyses the impacts of different transport policies on the structure of land development by applying general methods of economic appraisal. Some examples are Handy [40]; Hayashi et al. [41]; Curtis and Mellor [42]. In common, these studies questioned the effectiveness of transportation policies considering their impacts on land development processes and the urban form. There are also examples following the rules and principles of cost-benefit evaluation approach. Different country examples are given in van Wee et al. [43]; Janic [44]; Rus and Nombela [45]; Chester and Horvath [46]. The first three are examples of an economic appraisal of impacts of transport infrastructure on selected urban areas in Europe while the third focuses on economic assessment of a high-speed rail in US. Further to these, there are more general articles examining the impacts of transportation policies within EU or in an international context. Related research includes Bristow and Nellthorp [47] and Odgaard et al. [48] providing an overview of the national appraisal practices in EU countries. Other than this, there are also examples of worldwide comparisons of the countries according to their transport project evaluation methodologies. Hayashi and Morisugi [49] carried out such research covering the appraisal methods for transportation projects in the UK, USA, France, Germany and Japan. In common, these studies show that all the subject countries utilise variations of CBA, some of which are complemented by alternative evaluation methodologies in different stages of project evaluations. The common impacts and indicators utilised in this literature are essential for the current research as it provides a framework for the selection and evaluation of the impacts and indicators for sustainability evaluation of transport and land-use relationship in the GDR scenarios.

3. Methodology

3.1. The Study Area

The Greater Dublin Region (GDR) consists of not only the business and urban core of Dublin but also the surrounding Counties of Kildare, Meath, Wicklow and Louth (Figure 1). Ireland with a population in April 2016 was 4,761,865 with 44% of the State's total urban population lived in Dublin [50]. The region has a housing tenure model based strongly on home ownership and single-family housing. During the Economic boom from 1990, strong population growth and easy availability of credit allied with generous tax incentives fuelled a major property boom [51]. The region has a flexible and development led planning policy framework allied with direct local political power over the planning process and development control. Over time this has resulted in over-zoning pressures and overbuilding of housing outside main urban centres. This trend, combined with an underdeveloped public transit system for Dublin, resulted in extensive dispersed development leading the European Environment Agency in 2006 to describe Dublin as a worst-case example of sprawl (see also Nedovic-Budic et al. [52]; Ustaoglu et al. [53]).

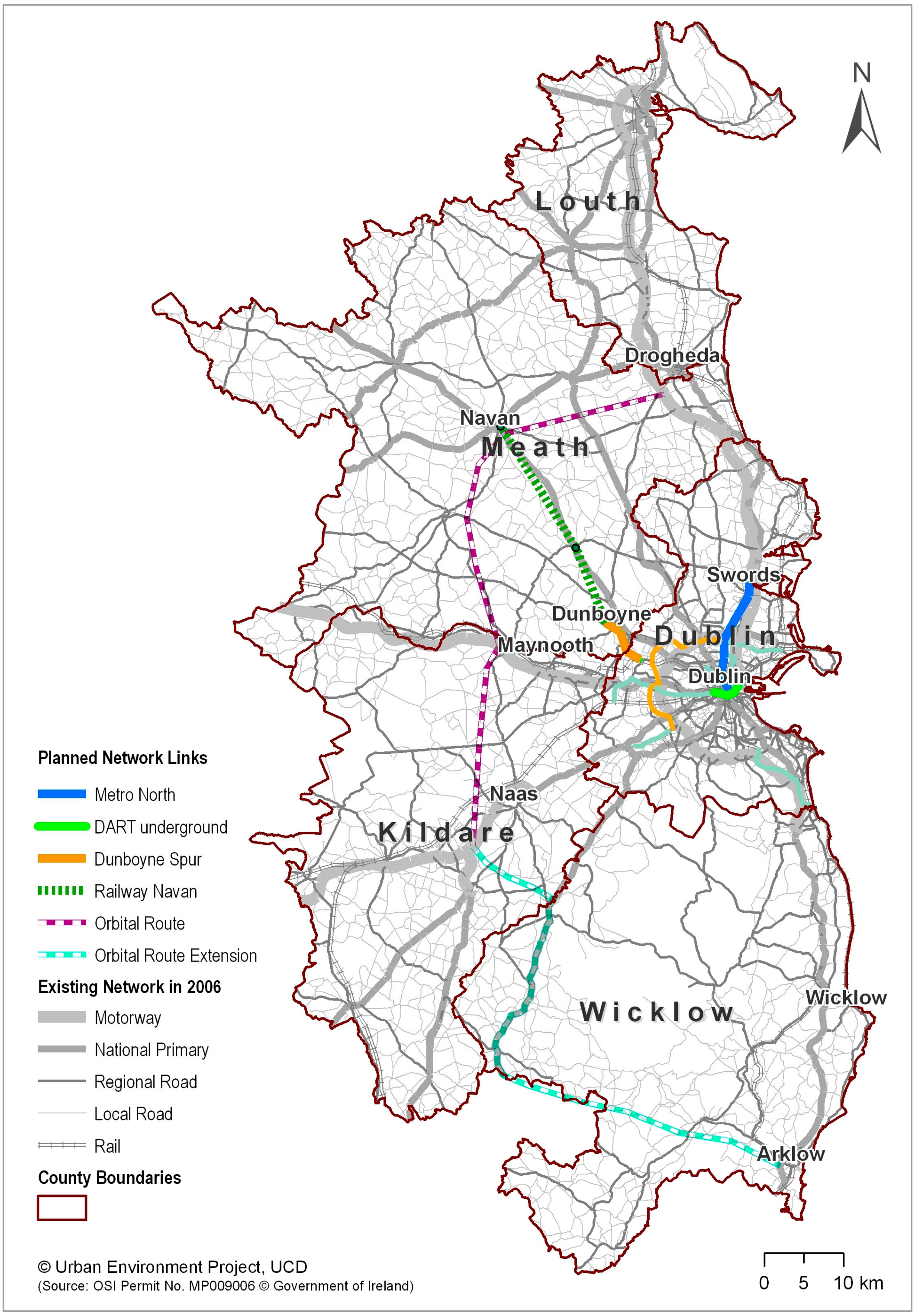


Figure 1. The GDR and Proposed Transport 21 Network Used in Scenario Applications.

The market imperfections, conflicts in the planning and administrative system and the rapid economic growth of 1990–2007 are the main contributory factors to dispersed or sprawl development patterns in the GDR, which can be characterised by single use and low-density developments. Such an urban development process can be identified as unsustainable considering wasteful consumption of scarce land and infrastructure resources; high infrastructure costs of servicing low density population;

and other undesirable consequences such as negative effects on the air and water quality, increased travel and accessibility costs and unwanted social equity costs. Here social equity refers to 'the state of affairs where all people within a specific society or isolated group have the same status in certain respects' (https://en.wikipedia.org/wiki/Social_equality). Given the definition of social equity, the literature suggests that higher levels of accessibility are associated with less spatial segregation, less income inequality and greater social capital [54,55]. By contrast, poor public transport accessibility, as in the case of dispersed development, can be a significant problem for certain socio-economic groups given that their low-income status and low automobile ownership make it difficult to afford high transportation costs. The low-income groups generally locate in the inner city and low-skill jobs tend to be located in the suburban areas, resulting in poor accessibility [56]. The distance to employment centres may lead to 'increasing unemployment rates among low-income residents and therefore increase poverty rates in the region as a whole' (Ewing et al. [56], p. 82). For a detailed literature review on the impacts of mobility on social equity, we refer to Ewing et al. [56].

Credible research demonstrated that more compact and mixed development patterns tend to improve community cohesion and low-income residents' economic opportunities by improving access to education, employment and public services [57]. In terms of sustainability implications, high quality and more efficient public transport provisions that responds economic needs and connects residents with jobs is considered as a key factor for city growth. For instance, Ewing and Hamidi [58] found that a 10% increase in the compactness index is associated with around 4% increase in residents' mobility. Additional studies have examined the relationship between urban crime rates and population density. A study by Browning et al. [59] focused on the link between urban density and violent crime rates in Columbus, Ohio and found that increasing urban density reduces the violent crime rates significantly. Hillier and Sahbaz [60] applied econometric estimation techniques to research the relationship between robberies and burglary and housing density in the selected neighbourhoods in London and confirmed that there is a negative association between residential density and crime rates. A further research by Ewing et al. [56] used structural equation modelling to research the relationship between urban sprawl and upward mobility. The latter term refers to individual's ability to move to a higher income level and social status. The study found that upward mobility is significantly higher in compact areas compared to dispersed areas.

Given the sustainability implications of land use-transportation relationship, the GDR requires further examination considering future land development processes and new infrastructure provisions within the context of sustainable urban development. In addition to this, the examination will also shed light on future planning decisions and new policy implications within the context of sustainable urban development. To provide transport infrastructure for the expanding population as well as pursuing sustainable development in the Region, central government introduced in 2005 a new transportation strategy for the GDR, which was known as the Transport 21 project (Figure 1). There was specific emphasis on the rail investments, in particular the Metro North project connecting Dublin centre with Swords, in order to achieve more compact and mixed developments along the rail lines and in urban centres. With the international Great Financial Crisis and property market collapse in Ireland, the Transport 21 plan was deferred in May 2011 and the Metro North Rail project was dormant for a number of years [51]. With the economic recovery and renewed concern at rising congestion levels in Dublin, this proposal was again under consideration in the Government's seven-year investment plan titled "Building on Recovery: Infrastructure and Capital Investment 2016–2021" (Transport October 2015) provided for a new metro project for Dublin, referred to as "New Metro North" (NMN), with passenger service expected to commence in 2026/27 [61]. The government represented by the Minister for Transport on 12 October 2017 as part its' budget of 2017 announced that the implementation of the project is to commence in 2021.

This paper focuses on sustainability of the land development and transport relationship in the GDR with a specific focus on various land development scenarios ranging from urban compaction (with rail) to dispersal (business-as-usual) and recessionary development. A CBA methodology is utilised for the scenario-based impact evaluation of Metro North investment linked with land development in the GDR.

3.2. The Urban CA Models and the MOLAND

The CA models have been the centre of computerised spatial modelling since the 1940s. The earlier versions of CA models were developed by Von Neumann in the 1940s which were improved by A. Burks in the early 1960s [62]. These researchers had shown the possibility of self-reproduction through the construction of a 200,000-cell configuration, which would reproduce itself. Some extensions of these models can be found in Schelling [63] and Wolfram [64]. The CA modelling of land-use change is under a developing progress since new developments take place in different directions. For instance, the CA modelling has been improved by integrating processes at multiple scales [65], incorporating economic principles in the CA rules [66] and modelling land-use-transport interaction [38].

The MOLAND Model is based on the CA developed by White et al. [67]. This technique involves a variety of inputs to determine the state of the land-use in each cell according to a set of transition rules representing the compatibility of land-uses with each other. At the regional level, there are four sub-models utilised in MOLAND and identified as [16]: (a) *regional economic sub-model* which calculates sector employment followed by a spatial allocation among the regions, (b) *regional demographic sub-model* which calculates the growth of regional population and allocates the regions housing demand, (c) *transportation sub-model* which is a four-stage model calculating the changes in traffic flows and the resultant impacts on land-use accessibility and inter-regional distances, (d) *land-claim sub-model* which translates the regional socio-economic growth numbers into a spatial representation for a further detailed allocation at the cellular (local) level.

The model has four parameters at the local level which are subject to CA modelling practice. These include: (a) *suitability* which refers to the degree to which a cell could support a particular land-use function and related economic/residential activity, (b) *zoning* which represents the institutional planning zones and the associated boundaries, (c) *accessibility* which represents the relative importance of each transportation link/node to each land-use class and (d) *neighbourhood (transition) rules* which determines the degree to which each land-use function is attracted to/repelled by each of the other functions present in the neighbourhood [68]. The model also includes a stochastic parameter which ensures the generation of realistic land-use patterns.

As in all CA models, a limitation of the MOLAND model is that the transition rules in the model do not include conflict resolving rules [69]. This is related to the collaboration and competition between human agents i.e., developers, firms, regulatory authorities, landlords, tenants etc. to change the urban area for their own purposes. This is to emphasise that transition rules should capture both locational preferences and behaviour of these spatial agents. Another shortcoming is the absence of mixed-zone classification within the MOLAND land-use classes. The model uses a classification of land-use types that are the same of CORINE Land-Cover European database but with a more detailed level of urban land-use classes [17]. Mixed-use of buildings and zones are a major problem concerning the transition rules utilised in the model. Transition rules have not been specified for mixed land-use classes to represent locational preferences of these land-uses in competition for space.

Another issue of concern is the accessibility parameters comprising weights between zero and one for representing the relative importance of several transport modes. These weights have been provided by the original developers of the model and utilised directly in the model as given. The absence of scientific method behind accessibility measures may lead us to conclude that the model lacks a theoretical background considering the accessibility parameters. Further to this, the model is designed to explain the intra-zonal accessibilities and does not consider the inter-zonal accessibility issues. The former represents the accessibility possibilities of various economic agents to the goods, jobs, services and markets within that zone while the latter points out the accessibility possibilities for those agents between different zones [70].

Even if the model is designed to explain intra-zonal accessibilities and exclude inter-zonal accessibility, there may be differences in the choice criteria of travel modes within a given zone varying with household's wealth, income level and preferences. In other words, high-income groups may give greater importance to quality highways and roads compared to low-income groups. The reason is related to high propensities of private car ownership among high-income groups and low-income groups' preferences in public transportation particularly bus and rail-based transportation [71]. As a result, these two different income groups may live in the same residential zone but may give different weights to different transportation modes. This concludes that household's characteristics should be combined with accessibility measures in relation with the specific transportation characteristics of the zones. As for any CA models [72], such limitations of the MOLAND model among others are of great significance to be tackled and still requires some further research for future development.

3.3. Application of the MOLAND Model in the GDR

The MOLAND model developed for the GDR has two components including regional and urban land-use sub-models. At the macro scale, the model allocates regional population and jobs among the counties. At the micro level, the provision for demographic and economic activities is translated into a number of land-uses i.e., the change in population is reflected in residential land-uses while the economic activity generated will affect commercial, industrial and service land-uses. The model includes an extensive data set covering the years 1990, 2000 and 2006 and utilises both macro and micro-type parameters. Macro-level data such as population and employment changes are inputs for the regional sub-model. The micro-model parameters (i.e., neighbourhood effects, suitability, accessibility, zoning, population, employment indicators etc.) are used to explain the micro-level spatial issues, which diverge the model from those incorporating aggregate data sets and relying on large geographic districts.

The initial stages for preparing land-use maps for MOLAND cover visual interpretation of aerial photography and satellite imagery. These were codified using the MOLAND classification system. The classification system is based on the European CORINE system [73] with some additional land-use classifications for particular urban areas (e.g., residential discontinuous sparse). MOLAND employs a minimum mapping area of 1 ha for urban areas and 3 ha for rural areas within the study region. There are 24 land-use classes modelled for the GDR within MOLAND applications [21]. Among them, 9 are classified as 'functions' considering their participation in urban growth (residential, industrial, commercial, services, port areas and construction sites), 8 are assigned to 'vacant' implying the areas where urban expansion actually takes place and 7 are 'features' which remain stable during the modelling process.

Initially a two-stage calibration was considered in the MOLAND applications: in the first stage, the model was calibrated by using 1990–2000 period data sets. This is followed by validation of the results using the 2000 and 2006 data as detailed in Shahumyan et al. [74]. The micro model (i.e., cellular automata) calibration process is based on a number of steps involving [75]: (1) Calibration of parameters defining the neighbourhood influence functions; (2) Calibration of stochasticity parameter α; (3) Introduction of sustainability, accessibility and zoning factors; (4) Fine tuning of the neighbourhood rules. The details of the application of calibration process can be seen in Shahumyan et al. [21].

3.4. Scenarios and the Land-Use-Transport Impact Assessment Methodology for the GDR

In this research, a variety of scenarios are considered in the GDR which takes into account both recovery and prolonged recession in the State's economy. Within the framework of this study, the transport-land-use relationship are evaluated considering various land development scenarios: (1) a baseline dispersed development business-as-usual scenario (2) a compact development with rail scenario and (3) a recessionary development with rail scenario, each simulated with the MOLAND model. The scenarios were originally developed for the forecast year 2026 representing an urban development during a 15-year period starting from 2011. On the other hand, the CBA evaluation of the scenarios is based on a 35-year appraisal considering that this is the official appraisal period for the major transport infrastructure programmes in Ireland. Figure 2 summarises the modelling and assessment framework utilised in this study.

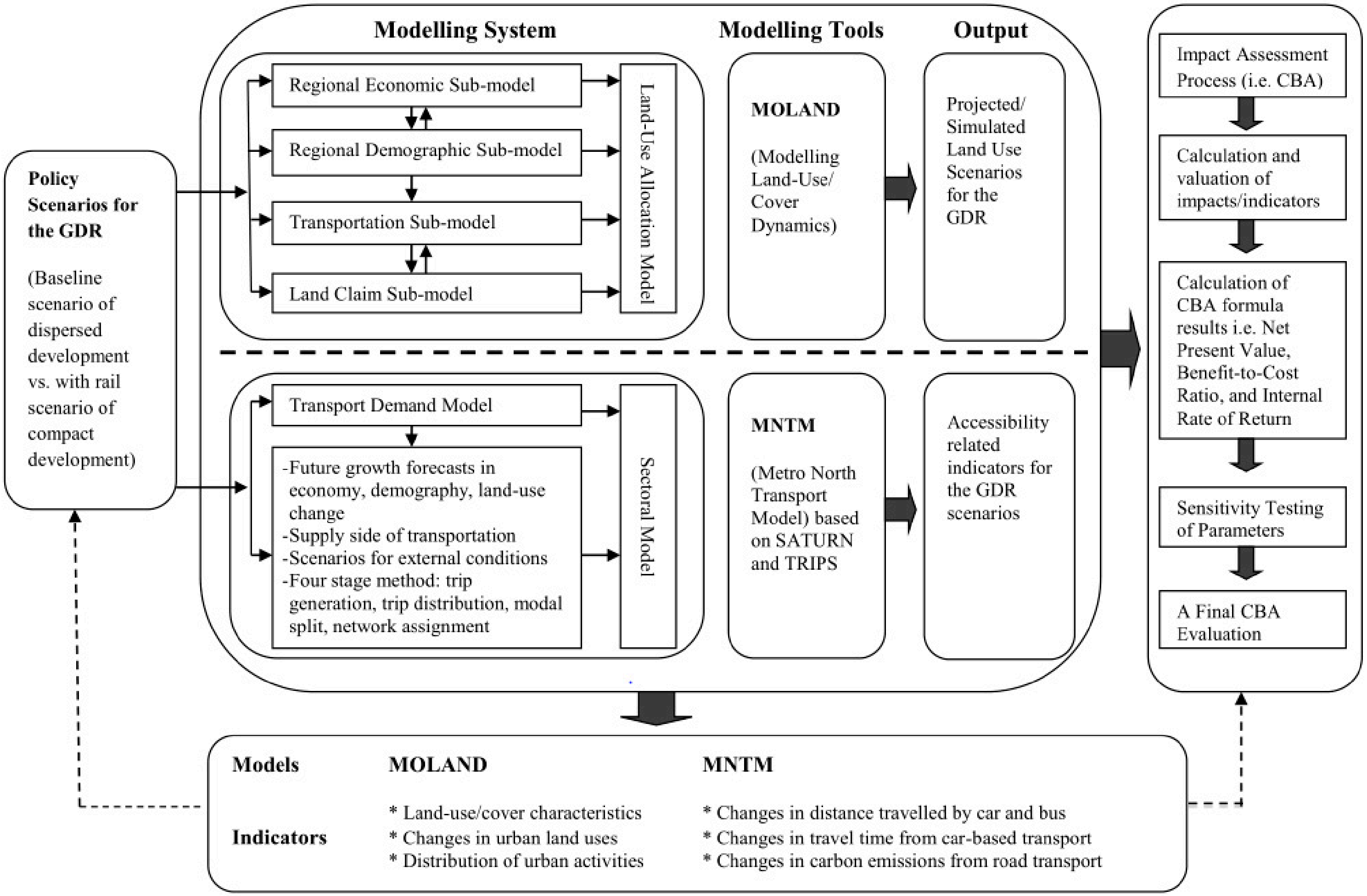


Figure 2. Summary of the Modelling and Assessment Framework.

3.4.1. Policy Scenarios for the GDR

The details of the modelled scenarios are shown in Table 1 and are summarised as follows:

Scenario 1: Business-As-Usual

In this scenario, current trends in land zoning, land development and transportation are continuing with new low density residential development taking place in the outskirts of the city and there are few improvements in regional and local roads with no new rapid rail infrastructure investment as provided by the Transport 21 project. Under this scenario, new residential constructions i.e., dispersed single-dwelling houses are emerged in the countryside resulting from limited integration in land-use/transport planning and weak environmental protection policies. This results in dispersed settlements around the GDR with high employment dependency on the core of the Dublin Area.

Scenario 2: Compact Development with Rail

This scenario is based on a more compact urban form compared to the baseline scenario considering that new high density residential development takes place inside the city and there is polycentric urban agglomeration associated with the provision of Metro North and other Transport 21 investments. This is in line with the evidence from the literature suggesting that rail-based transportation tends to encourage more compact and mixed-use developments in new areas of urban growth particularly when supported by strategic transport-land-use planning and urban compaction policies [76]. The integrated planning in transport and land-use could support developments such as self-sufficient towns along newly provided public transport corridors limiting the number of commuting trips to the central Dublin Area. This implies that dependence on the Dublin city centre is less than those in the *business-as-usual* scenario which may result in less traffic congestion and reduction in some other costs of travel. This may include increase in access to urban activities i.e., jobs, public services, recreation etc., benefits from access to multi-modal travel options i.e., walking, cycling etc. and reductions in transport-related emissions and pollution.

Scenario 3: Recessionary Development

An alternative scenario is the prolonged recession case which considers the prolonged impacts of the economic crisis in the GDR. This scenario is characterised by a decline in demand for new residential development as a result of the reduction in economic activity. New small-scale housing takes place in the countryside but in limited numbers. This will result in dispersed development but at a moderate level compared with the urban dispersal in the continuous economic growth case. The Metro North project was the only project identified as likely to take place in this scenario considering that the project will be funded by the Government irrespective of the current economic climate which is assumed to be less influential on the initiation of the project but has a major impact on cost-benefit analysis.

Table 1. Characteristics of the Urban Development Scenarios in the GDR.

	Business-As-Usual Scenario:	**Compact Development with Rail Scenario:**	**Recessionary Development Scenario:**
	Continuous Economic Growth	**Continuous Economic Growth**	**Prolonged Recession**
Population	Steady population growth: - In migration of young - Increased fertility rates	Steady population growth: - In migration - Increased fertility rates	Moderate population growth: - No immigration - Increased fertility rates
Economic Trends	- Steady increase in GDP - Investments in manufacturing, human capital, high tech sectors, agriculture - Increase in exports - Local products are being more promoted - Tourism, agro-tourism and service sectors (health care, public transport, accessibility to public green space, accommodation, food and beverage, entertainment etc.) are strongly encouraged	- Steady increase in GDP - Invest more in: manufacturing and human capital - More people employed in science and research - Continued investment in high-tech sectors which concentrated in existing urban environment - Exports are highly encouraged - Reinforcement of agro-tourism	- A decline in GDP followed by economic stagnation or a modest increase by the end of crisis - Either no new investment or very few developments in manufacturing, human capital, high-tech sectors and agriculture following the economic stabilisation - During a recession, there is an increase in imports and decrease in exports and the balance can be stabilised at the end of the recession - Tourism, agro-tourism and service sectors are in decline
Spatial Development/ Planning	- New constructions occur in rural hinterland - Improvement of urban infrastructure (roads, information networks, sports/recreation, stores)	- Polycentric urban agglomeration associated with the conservation/restoration of existing buildings - New residential development inside the city–increased density by multi-stories buildings	- Decline in demand for new development - New residential development in the country side but in very limited numbers - Increase in vacancy rates with many constructions left unfinished
Transport	- Improvement of regional and local roads - Better links to the motorways and airport extensions	- Public transport is encouraged - Investment in Metro North in 2014 - Investment in other Transport 21 railways in post-2020	- Investment in Metro North potentially in 2014 - No investment in other Transport 21 railways
Overall Trends	- Economic growth - Low environmental protection - Dispersed single-dwelling housing growth in the country side	- Economic growth - High environmental protection - Self-sufficient towns limiting commuting to Dublin Area	- Economic stagnation - Low environmental protection - Small-scale housing growth in the country side

3.4.2. Evaluation Methodology for the Transport-Land-Use Impact Analysis of the Scenarios

The selection of related indicators for this study is based on common impacts and indicators given by the relevant international literature (see Hayashi and Morisugi [49]; Janic [44]; Odgaard et al. [48] among others). In this, four main types of criteria pointing to transport infrastructure provision impacts are specified as: direct changes of land use (development costs/capital investments of rail infrastructure, greenfield land values), changes in development patterns (costs of providing public services), changes in land-use accessibility and transport diversity (road vehicle operation costs, travel time, accident costs, rail operating costs and revenues, area property values (In relation to area property values, there are two key points to highlight: First, the land value-gains accrue to private property owners to a large extent. Second, it is important to mention the existence of relocation effects stemming from local development i.e., the gain achieved by one area may be lost in another area in the region implying a net zero effect overall. Therefore, it is suggested that effects on local development reflected in adjusted property values are not to be taken into account in CBA but can be evaluated separately subject to a qualitative assessment.) and changes in travel activity (CO_2 emissions and local area pollution), as suggested by the international literature. Data limitations for the impact evaluation of rail investments in the GDR are also influential in the process of the selection of indicators. Metro North project is selected for the scenario-based impact assessment in this study, considering its wide impacts in the GDR and in particular, data availability for this project published in various sources.

From the literature review, there are few studies with a capacity of incorporating all of the possible externalities into their analysis. This stems from the fact that it is difficult to quantify most of the impacts of transportation provisions. Some of the impacts and indicators can be represented in monetary values while others can be only expressed in a qualitative way. There may be also correlations among various indicators such as the positive correlation between land-use accessibility and land values, or the negative correlation between air pollution exposure and area property values. Considering the correlation effects, data limitations and the marginal role of some specific impacts in CBA, only a limited number of indicators are selected in the present analysis.

A CBA approach which is based on a straight net present value calculation is considered appropriate for the scenario-based evaluation of the transport-land use impacts of rapid rail investment in the GDR. In CBA, all costs and benefits are reduced to their present value and discounted at a standard rate over the pre-specified evaluation period through the formula given below:

$$ENPV = \sum_{t=0}^{n} a_t S_t = \frac{(b_0 - c_0)}{(1+r)^0} + \frac{(b_1 - c_1)}{(1+r)^1} + \ldots + \frac{(b_n - c_n)}{(1+r)^n} \quad (1)$$

where S_t is balance of cash flow funds comprising flow of benefits, b_t and flow of costs, c_t; a_t is discount factor, r is discount rate and n is the evaluation period [77]. This is also used to produce a benefit-cost ratio (B/C) and internal rate of return (IRR). The former is the ratio of the discounted aggregate net benefits (i.e., benefits minus costs) to the discounted investment costs and the latter is the rate of discount equating discounted net benefits to discounted investment costs.

For the Cost-Benefit impact assessment of transport-land-use relationship of the *business-as-usual* and *with rail* scenarios, the selected indicators were monetised and assessed following the methodology on the monetisation and valuation of the transport-related indicators reported in various sources. Given this literature, the impact evaluation data is identified and utilised regarding the selected indicators in this study and summarised in Table 2.

Table 2. Impact Evaluation Data for Rail-Based Infrastructure Investments: With-Rail vs. Business-as-Usual Scenario Approach.

Impacts/Indicators	Impact Evaluation Data of With-Rail Scenario vs. Business-as-Usual Scenario
1. Capital costs of rail infrastructure investment	Direct construction cost estimates include the following: Land acquisition costs, railway infrastructure, stations, civil engineering works, operational systems, planning and design. Source: RPA [78].
2. Greenfield land values	Total amount of greenfield land within 1km catchment area of Metro North and estimated change of the value of greenfield land across *with rail* and *business-as-usual* scenarios. Source: RPA [78].
3. Provision of public services	- Future estimated numbers for population and new residential development (numbers of new housing units) in the case study area within the appraisal period specified for rapid rail investments. Source: CSO [79]. - Public service provision costs (e.g., school transportation costs, electricity connection and distribution costs). Source: Department of Education and Science, Ireland, Ref. [80]; ESB Networks Ltd. Statement of charges [81].
4. Accident rates/future accident risks and accident costs	Three types of data are specified: - The most recent data related to the number of personal fatality, serious injury and minor injury accidents along the catchment area of the newly proposed rail line. Source: RPA [78], - Estimated numbers for future accident risks from the national and local accident rates and trends, - Quantification of changes in the number of fatalities, serious injuries and slight injury accidents due to a rapid rail investment by using country specific risk functions, - Road accident costs by type of accident were adapted from the study of Goodbody Economic Consultants Report [82].
5. Change in road vehicle operation costs	For the calculation of the economic benefits (costs) associated with vehicle operating costs, three types of data were utilised: - *Demand*: number of private (cars) and public (bus) vehicles making a particular origin-destination trip for the business-as-usual scenario and the alternative with rail scenario (peak/off-peak traffic flow data for the baseline and alternative scenarios), - *Vehicle kilometres*-total change in vehicle kilometres from the local highway network for the business-as-usual and with rail cases, - *Operation costs:* fuel cost and non-fuel cost parameters were obtained from UK Department for Transport [83] and adapted to the Irish case following Goodbody Economic Consultants Report [82].
6. Change in travel time	Estimates related to: - *Travel time*-change in travel time for private (cars) and public (bus) vehicles in peak/off-peak traffic for the business-as-usual and with rail scenarios, - *Demand*: peak/off-peak traffic flow data for the business-as-usual and with rail cases, - *Value of time:* The proxy for the value of work time is the average wage rate plus an allowance for employment related overheads. The non-work value of time used in the UK was adapted in the current study, representing 40 percent of the mileage weighted hourly earnings of commuters [84].
7. Rail operating costs and revenues	- Expected operating pattern and service frequency of newly proposed Metro North, - Key characteristics (route length, journey time, peak and off-peak headway etc.), - Estimated annual operation cost and revenues. Source: RPA [78].
8. Change in CO_2 emissions	- Total change in greenhouse gas emissions (i.e., CO_2, in particular) for the business-as-usual and with rail cases, - *Social cost of carbon:* The CASES Project [85] recommends using the carbon prices obtained by DEFRA [86] as a central estimate for the price of global carbon emissions as this is the most recent policy oriented study on the social costs of carbon. This is considered for the current study.
9. Change in local area pollutants	- Total change in local area pollutants (CO, NO_x, UHC-Unburned Hydro Carbons) along the Metro North corridor for the business-as-usual and with rail cases, - Cost factors for local area pollutants are from HEATCO [87] and UNITE [88].

4. Results

4.1. Results from the Scenario Analysis

Given the storylines outlining different scenarios (Table 1), MOLAND Model was run for the scenario analysis to explain spatial variations in the GDR pointing the differences in the scenario storylines. The three scenarios were developed towards 2026 and named according to the characteristics demonstrated in the scenario storylines. The variations of urban development for each of the three scenarios are shown in Figure 3. From the figure, the differences between the scenarios are very clear: in Scenario 1, the GDR has experienced residential development some part of which is in the vicinity of the existing urban area and some other parts are scattered across the region in many small clusters. Scenario 2, on the other hand, achieves more concentrated urban growth which is consolidated within a number of growth centres and towns. Scenario 3 has region-wide dispersion of residential development, though the volume and the scale of development is smaller compared to other two scenarios. A further analysis was carried out taking into account the classification of the urban cells in the GDR scenarios. There are four different land-use classes considered for the comparisons in urban cell counts for the post-2020. These include: residential, commercial, industrial and services. The variations in urban land-use according to the scenarios in the GDR counties are provided in Figure A1 in Appendix A.

From the findings in Figure A1, it is evident that Dublin requires large amounts of infrastructure development given the high shares of new residential, industrial, commercial and services developments over the recent period. The findings from scenario analysis also confirm that industrial and commercial infrastructure requirements are more intensive for the economic growth scenarios compared to the recessionary development case. Unlike commercial and services sector developments, industrial developments are likely to be agglomerated in various locations for both dispersed and compact development scenarios under economic growth conditions. This implies that industrial infrastructure provision can be more efficient and less costly considering the agglomerations in these locations. Services and commercial developments are highly scattered in both dispersed and compact development scenarios of economic growth. It is likely that these developments are taking place either in urban centres or close to the existing urban areas along major transportation networks. Therefore, they can benefit from existing urban infrastructure provided in the area with less demand for new infrastructure provisions.

A general summary table is also provided showing land-use types and their corresponding areas along the catchment of Metro North alignment for both with rail and business-as-usual scenarios (Table 3). These results represent the outcomes of the MOLAND modelling work concerning both scenarios (i.e., with rail and baseline) developed for the GDR along the 1 km catchment area of Metro North. From this table, there are increases in the areas of following land-uses considering a shift from baseline to with rail scenario: residential continuous dense urban, residential discontinuous sparse urban, commercial areas, public and private services and pastures. By contrast, areas of residential continuous medium dense, residential continuous urban fabric, industrial uses, arable land and heterogeneous agricultural uses would decline with a shift from baseline to with rail case.

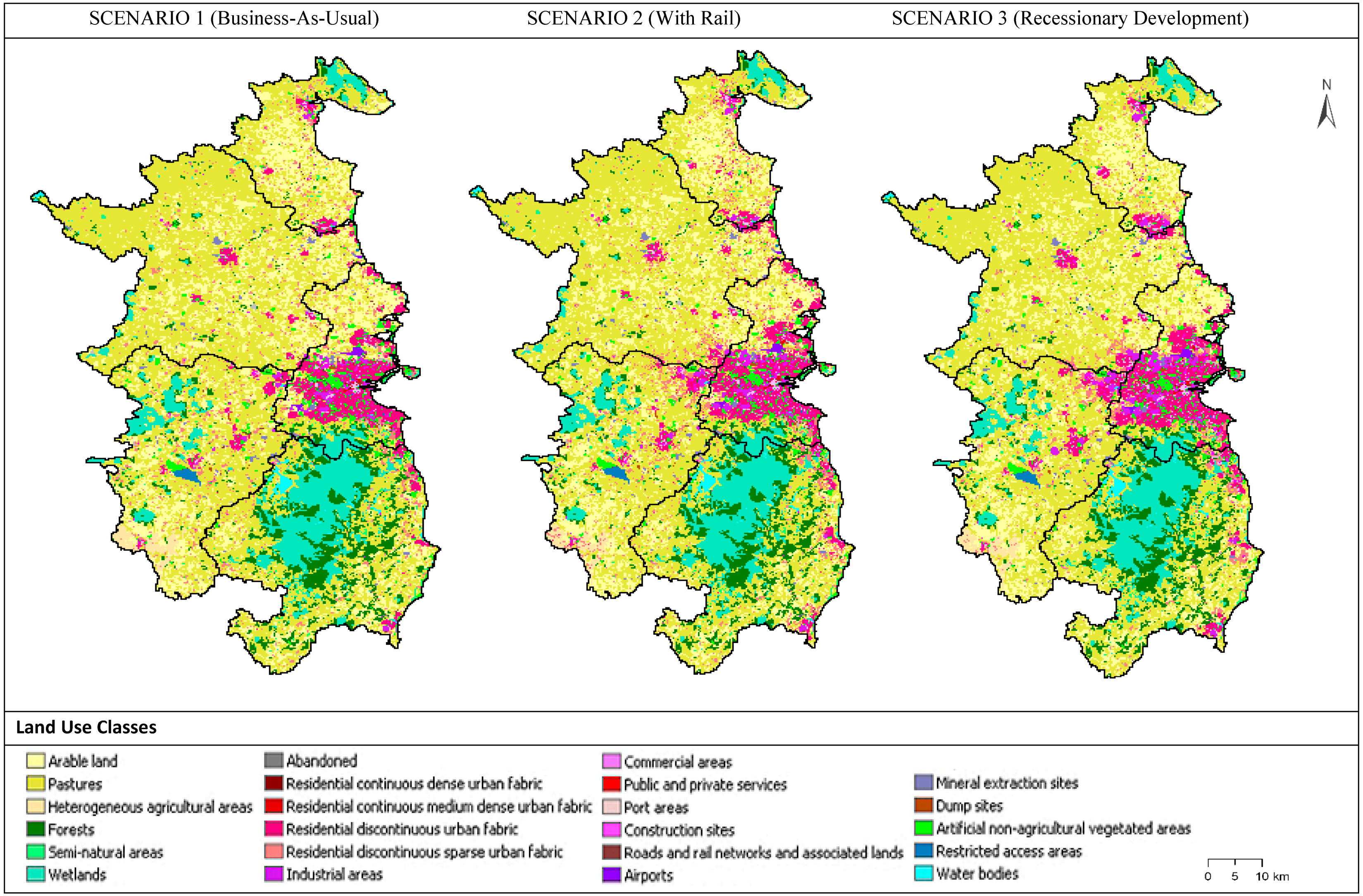


Figure 3. Land Use Scenarios Developed for the GDR.

Table 3. Change in Land Uses along the 1 km Metro North Catchment Area for the Baseline and With Rail Scenarios.

Land Use Types	Land Area (in ha)		% Change in Land Area from Baseline to with Rail Scenario
	With Rail Scenario	Baseline Scenario	
Residential continuous dense urban	24	16	+50%
Residential continuous medium dense	104	156	−33.3%
Residential discontinuous urban fabric	484	444	−9.1%
Residential discontinuous sparse urban	68	60	+13.3%
Industrial areas	136	140	−2.9%
Commercial areas	244	240	+1.6%
Public and private services	164	144	+13.8%
Arable land	4	8	−50%
Pastures	76	68	+11.8%
Heterogeneous agricultural areas	28	56	−50%

Source: Urban Environment Project, UCD.

4.2. CBA Results

In accordance with the estimations from the Metro North Transportation Model (MNTM) (MNTM was developed by the Rail Procurement Agency, Ireland to assess existing traffic conditions within Dublin and particularly along the catchment of Metro North. It is a SATURN and TRIPS based traffic model where private transportation is modelled utilising the SATURN software (Atkins Limited, Surrey, England) and public transport side of the trip demand is modelled with TRIPS.) (Figure 2) and the parameters/values specified for the capital costs, costs of accident, vehicle (and system) operation, public service provision, travel time and carbon dioxide and local area pollutants, the balance of cash flows for each year starting from 2011 were computed in the first stage. In the initial research, the period 2011–2015 was the assumed construction period for the Metro North Project, 2016 was the first year of metro operation and 2029 was the forecast year in which the whole Transport 21 programs [89] were assumed to be carried out. The balance of cash flows representing net total revenues over total costs were utilised for the computation of Expected Net Present Value (ENPV) by applying the formula given in (1). For the discounted cash flow analysis, a 35-year period is chosen starting from 2011 and ended in 2045 [90]. All the values were calculated considering five different discount rates of 3.0%, 3.5%, 4.0%, 4.5% and 5%. Among these, 4% is considered as the official discount rate as it is commonly used in transport project and programme evaluations in Ireland [90,91].

Table 4 shows that benefits of the Metro North scheme can only be seen after 35 years of operation as indicated by supportive findings from ENPV, B/C and IRR formulas. Thus, net benefits exceed the costs within 40 years of appraisal. By contrast, the results obtained for 30 and 35 years of appraisal indicate negative ENPV, benefit-to-cost ratios lower than 1.0 and IRR lower than the discount rates considered in the analysis. If the results are based on 35 years of evaluation (i.e., the official appraisal period), it is clear that ENPV is negative across all the different discount rates and there are also benefit-to-cost ratios lower than 1.0 for each of the discount rates. IRR is 3% indicating net discounted benefits are about to exceed the costs only computed with a discount rate of 3%. These findings imply that through 35 years of evaluation, CBA results do not support the *with rail* scenario as associated with the Metro North infrastructure investment in the GDR. In fact, the benefits of the *with rail* scenario can be seen in the longer term as indicated by supportive findings obtained for over 40 years of appraisal in Table 4.

Table 4. Net Present Value of Costs and Benefits as at 2010.

Discount Rate	ENPV	B/C Ratio	IRR	Evaluation Period
45 YEARS OF APPRAISAL (5 years construction + 40 years operation)				
3.0%	553 million €	1.28	0.04166(4%)	2011–2055
3.5%	289 million €	1.15		
4.0%	64 million €	1.03		
4.5%	−126 million €	0.93		
5.0%	−289 million €	0.85		
40 YEARS OF APPRAISAL (5 years construction + 35 years operation)				
3.0%	242 million €	1.12	0.03596 (4%)	2011–2050
3.5%	36 million €	1.02		
4.0%	−141 million €	0.93		
4.5%	−293 million €	0.85		
5.0%	−425 million €	0.78		
35 YEARS OF APPRAISAL (5 years construction + 30 years operation)				
3.0%	−68 million €	0.97	0.027960 (3%)	2011–2045
3.5%	−222 million €	0.89		
4.0%	−356 million €	0.82		
4.5%	−473 million €	0.75		
5.0%	−575 million €	0.70		
30 YEARS OF APPRAISAL (5 years construction + 25 years operation)				
3.0%	−380 million €	0.81	0.01607 (2%)	2011–2040
3.5%	−487 million €	0.75		
4.0%	−582 million €	0.70		
4.5%	−666 million €	0.65		
5.0%	−740 million €	0.61		

As discussed previously, we evaluated expected changes of the greenfield land values separately considering the issues of double counting in the CBA results. Following the construction of Metro North, the estimated increase in the value of greenfield land per hectare for different areas along the catchment of Metro North and the total numbers of change computed for the whole area is given in Table 5.

Table 5. Annual Expected Changes in the Greenfield Land Values within 1 km Catchment Area of Metro North.

Total Amount of Greenfield Land	Expected Change in Annual Value per hectare of Greenfield Land in Business-As-Usual vs. with Rail Scenarios *	Expected Change in Total Greenfield Land Values, in €
254.1 ha	Price rises from 60,000 €/ha to 1,500,000 €/ha implying a net change of 1,440,000 €/ha.	365,904,000 (=254.1 × 1,440,000)

* Source: Publicly available data of auction and transaction sales which had been tested by consultations with property market experts.

The distribution of cost and benefits (in 2010 prices) in the overall cost-benefit value is shown in Figure 4. Travel time and public service provision costs have similar shares i.e., 1.43% and 1.25% respectively in contributing the overall value. Metro operation costs have 4.6% share in the overall CBA achieving greater contribution than savings in travel time and public service provision costs. Further to this, capital costs and metro operation revenues account for the highest shares while cost savings in accidents, vehicle operation and air pollution comprise the lowest shares in the overall CBA value.

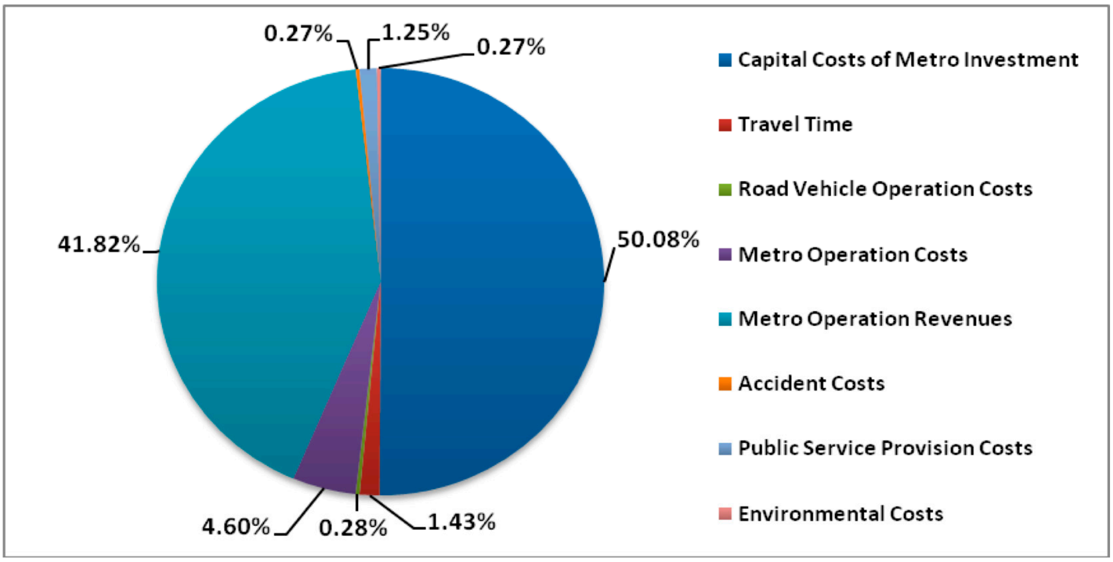


Figure 4. Distribution of NPV (2010 Prices). Note: A 35-year appraisal period and 4% discount rate is applied.

The key purpose of the most transport investments, particularly the rapid rail infrastructures is to reduce the time it takes to travel from one place to another [92]. Rapid rail projects are also intended to reduce various costs to users including vehicle operation, safety, environmental costs and others. There are international examples of rail transportation appraisal work verifying that main benefits of rail transport investments comprise travel time and cost savings (user and agency) and accident reduction [49,93]. By contrast to these research findings, Figure 4 shows that cost savings in travel time, vehicle operation and accidents have a lesser than expected impact on the overall cost-benefit value. From these figures, metro operation revenues are the primary source of benefits accrued to Metro North investment. The estimated parameters used to calculate the subject indicators, particularly the transport-related indicators are coming from secondary sources such as the MNTM and the analysis carried out by the RPA [78] for the estimation of the operation revenues of Metro North. These unexpected findings can be related to the existence of bias or estimation errors either in the transportation modelling process or with the estimation of the metro operation revenues. Further research can be suggested for a detailed analysis of the subject parameters utilised in the calculation of transport-related indicators and metro operation revenues.

Transportation related indicators i.e., travel time, road vehicle operation costs and accident costs are analysed in detail based on the variation of NPV of the subject indicators in peak and off-peak hour assessments. The NPV results are presented in Figure 5 for peak and off-peak hour variations in travel time, fuel and non-fuel vehicle operation costs and accident costs. In relation to savings in travel time and vehicle operation costs, peak hour totals show considerable contributions to the savings while off-peak hour totals are dramatically small in value compared to peak hour counterparts. This may have three implications: First, people shift to metro as a means of fast and more convenient means of transportation compared to private car during the peak hours. Second, there is less traffic congestion on the road network as a result of the shift to metro in the peak hours implying more savings in travel time and vehicle operation costs in the road transportation. Third, there is an increasing tendency among people to use private car-based transportation during the off-peak hours which leads to an increase in the number of cars on the road network. It was noted that travel time and vehicle operation cost savings were underestimated during off-peak periods considering the MNTM estimations indicating very small and negligible differences in time and distance travelled by private cars between the baseline and with rail scenarios. This seems to be unreasonable considering that there is possibly an increasing demand during both peak and off-peak periods for the use of metro thanks to the existence of Dublin Airport. Therefore, some related adjustments were made in the sensitivity analysis for the off-peak hour estimates to represent these expected shifts from private to public transportation. This sensitivity analysis applied to travel time and vehicle operation costs is not within the scope of this paper. For the details of the sensitivity analysis, we refer to Ustaoglu [94].

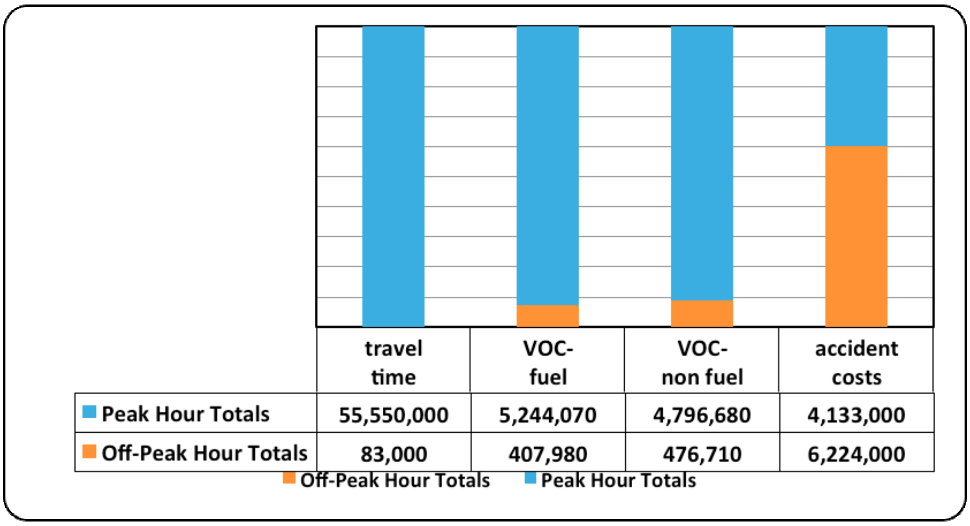


Figure 5. Distribution of ENPV of Travel Time, Road Vehicle Operating Costs (VOC) and Accident Costs across Peak and Off-Peak Hour Totals. Note: A 35-year appraisal period and 4% discount rate was applied.

Unlike travel time and vehicle operation indicators, accident cost savings are higher in off-peak hours compared to peak hour totals. The reason is related to increased average speeds on the road network during the off-peak hours as a result of a reduction in traffic congestion. Baruya and Finch [95] showed that lower average speeds are associated with larger speed variance and is related to a higher crash rate in comparison with higher average speeds. This implies that higher average speeds during off-peak hours result in low speed variance and a lower crash rate when compared to lower average speeds of peak hours. The result is higher savings in accident costs during off-peak time than those obtained for peak totals.

A more recent study by National Transport Authority Ireland [96] provided a cost-benefit assessment of the Metro North project with various amendments to the scheme including fewer stations, vertical alignment changes, smaller stations and change in quantity of rolling stock. Because of the impact of economic recession on population and employment, there would be reductions on passenger demand for the future transport network. On this basis, the capacity requirement of Metro North was reduced and the original metro scheme was amended. The findings of NTA's [96] cost-benefit assessment of Metro North project will be compared with the findings of the current study (Table 6).

Table 6. Evaluation of Cost-Benefit Assessment Results.

Description	Findings from Current Study	Findings of NTA (2015)
	Full Scheme 2045 (€ Thousand, 2010 Prices)	**Full Scheme 2033 (€ Thousand, 2009 Prices)**
Total costs	2,140,762	1,026,853
Total benefits	1,999,746	1,562,716
Economic Net Present Value (ENPV)	−141,000	535,863
Benefit-to-cost ratio (B/C)	0.93	1.5
Discount rate	4%	NA

From Table 6, it can be noted that the metro scheme that was amended through the reduction of system capacity resulted in a positive ENPV and a B/C greater than 1.0. By contrast, the original scheme as considered in the current study has a negative ENPV and B/C less than 1.0. The lowest levels of capital costs and operation and maintenance costs arise from the amended metro scheme which would have a shorter alignment and fewer stations. Compared to the original metro scheme, the lower levels of costs and higher levels of benefits would deliver higher levels of benefits in the case of the amended scheme. Considering the differences in the evaluation periods, the results show that the highest level of benefits are realised at an earlier date in the amended metro scheme as the delivery of the full scheme is by 2033 while benefits in the original scheme could be achieved over a longer period (as the original scheme is delivered by 2045).

Other than the impacts which are monetised in the current study, there are also benefits of public health and induced benefits of safety, both are resulting from the provision of rapid rail system that is associated with compact development policies. Travel activity has impacts on public health as it causes more than 60% of total potential years of life lost [97]. A major health impact of transportation is on physical activity and fitness. The literature argued that inadequate physical activity leads to obesity, which contributes to hearth and vascular diseases, strokes, diabetes, hypertensive diseases, osteoporosis, joint and back problems, cancer and depression [97,98]. Related research suggests that obesity rates tend to be inversely associated with the use of alternative modes of transportation (e.g., walking, cycling, public transit) [99,100]. There is substantial body of literature claiming that compact urban development leads to an improvement in physical fitness and health considering that mixed land-use development improves walking and cycling conditions and encourages the use of these modes for both commuting and recreation purposes [58,101,102]. For instance, Frank et al. [103] found that residents of the mixed land-use neighbourhoods walk, bike and transit 2–3 times more and drive almost 60% less compared to those living in more sprawled and automobile-oriented areas. A study by Giles-Corti et al. [104] indicated that overall health of residents improved if they moved from dispersed to more compact, walkable neighbourhoods. Sarkar et al. [105] found that there is positive association between healthy weight and walkability; and therefore, higher residential density has beneficial effects on accumulated physical activity.

The service quality of transport system has impacts on mental health because high quality public transit systems can reduce emotional stress by improving accessibility to education, social, recreational and employment activities, improving community cohesion and reducing insecurity and crowdedness at transit stops and in transit vehicles [97]. Increased walking and cycling activities can reduce stress and depression because many commuters find alternative modes of travelling less stressful than driving [106]. Though mental health impacts of public transit systems are significant, it is difficult to measure and monetise them [97]. By contrast, the physical health benefits associated with public transit provision can be monetised through computing the value of reductions in hearth disease, hypertensive diseases, diabetes, congestion and pollution. An alternative approach is to compute total savings from medical expenditures resulting from increased physical activity. The data on values of health benefits and medical cost savings are not available for the Greater Dublin Region. Based on the availability of such data, health benefits can be included in the cost-benefit analysis framework as a future research focus.

A further category of health impacts of transportation system is injuries, disabilities and deaths resulting from traffic crashes on transport network. There are various studies in the literature asserting that the density of road network, transit stop and mixed land-use developments increase the likelihood of traffic accidents [107]. Although crash rates increase with population densities, it can be argued that crash severity and casualty rates (injuries and deaths) are higher in dispersed areas due to higher speeds and slower emergency response [97]. The supporting literature states that rapid rail investments associated with compact development policies reduce traffic speeds and total vehicle traffic due to a shift from road vehicles to the rapid rail transport and improves emergency response and travel options that help reducing higher risk driving, traffic accidents and crash fatality rates [58,108]. In the current study, traffic safety is evaluated through computing cost savings of traffic accidents on the road network in comparison of with rail scenario with the alternative scenario of dispersed development. In addition to this, the impact of comfort and safety provided by rapid rail transit systems should be evaluated within the cost-benefit evaluation framework. Public rail transit is relatively safe mode compared to car-based transportation considering that rail transit travel has lower fatality rates than automobile travel [109]. Ewing et al. [99] found that traffic fatality rates are lower for the mixed land-use developments that offer alternative modes of transportation compared to those of automobile-oriented sprawled developments. The overall health impacts of public rail transit system are summarised in Table 7.

Table 7. The Health Impacts of Rail Transit Systems.

Health Benefits *	Rail Transit Impacts *	Impact Evaluation Criteria	Expected Impacts of Metro North
Traffic safety. Reduced traffic crash injuries, disabilities and death on the road network	Reductions in traffic injuries and deaths resulting from shifts from road transportation to rail transit system	Accident cost savings from death and injury traffic crashes	Reduction in traffic accidents and related costs along the Metro North catchment area as Metro North will provide a reduction in car-based trips
Pollution reduction. Reductions in air, water and noise pollution	Reductions in traffic induced emissions and noise following a shift from car-based transport to rail	Savings in Greenhouse Gas (GHG) emissions, savings from local air/water pollutants and savings from noise pollution	The introduction of Metro North to the network will introduce a new pollution source to the Metro catchment area. However, there will be an overall reduction in the pollution levels due to reduced traffic on the road networks
Improvement in physical fitness. Increased physical activity by walking and cycling	Rail transit oriented development improves alternative modes of transport (walking, cycling), which tend to increase physical fitness	Savings from medical expenditures resulting from increased physical activity, value of reductions in hearth diseases, hypertensive diseases, diabetes and others	Recent policies and plans introduced in anticipation of Metro North support mixed land-uses of medium to high-density developments within the Metro North catchment area. Metro North enhances transportation diversity in the GDR and supports walking, cycling and other transport modes. There will be overall reduction in health costs as a result of improvement in physical activity by walking and cycling
Mental health. Reduced emotional stress	High quality rail transit systems and transit oriented development provide comfort and reduces emotional stress and provide access to social, economic and recreational opportunities	Cost savings from medical expenditures related to emotional stress and depression	It is estimated by the RPA (2010) that a considerable proportion (around 12 million) of car trips per annum will be reduced from the highway network following a shift to the Metro system. Metro North provides a high-quality transportation option. It is expected that this will reduce emotional stress and associated health costs
Affordability. Reduced financial burdens, particularly for lower income residents	Rail transit and transit oriented development reduces cost of transportation, which leaves money to purchase housing, healthy food and medical care	Cost savings from transport-related expenditures	Metro North provides a cheaper transportation option compared to automobile-oriented transportation, particularly along the catchment of Metro North Line. This will reduce the costs of transportation and supports incomes of residents
Basic mobility. Improved accessibility to essential goods and services	Rail transit and transit oriented development improves mobility and locational accessibility	Changes in accessibility of land-uses following the provision of rail transport system	Metro North will provide the required transport options to the existing residents to reach to key employment, social, recreational and other services in the GDR. Hence it improves accessibility of various goods and services

Note: * Source: Litman [97].

Further impacts of transit-oriented development associated with compact development policies include reductions in land and energy consumption, ownership of fewer private vehicles, reduction in parking costs, requirement of less parking space and consequential reductions in traffic congestion, traffic risks and traffic impact fees [110]. In the suburban areas that are in the outskirts of the central core, there are low-density single land uses, abundant and unpriced parking facilities [111]. By contrast, in the higher density areas of more compact developments, there is lower parking supply and higher parking prices [111]. Transit-oriented development encourages multi-modal uses of transportation and hence reduces vehicle ownership and use. This in turn reduces road space required per capita and improves parking facilities to serve multiple destinations, which overall reduce total road and parking land requirements [111,112]. Research suggests that automobile-oriented travelling requires more space than other modes of transport (Figure 6). The reason is twofold. First, road transportation vehicles require more distance from other objects, including wider lanes and more distance between vehicles [113]. Second, road vehicles also require parking spaces at destinations [111]. By contrast, pedestrians and public transit users do not require parking space and there are plenty of free parking spaces for bicycles that require considerably lower parking space compared to one car [113].

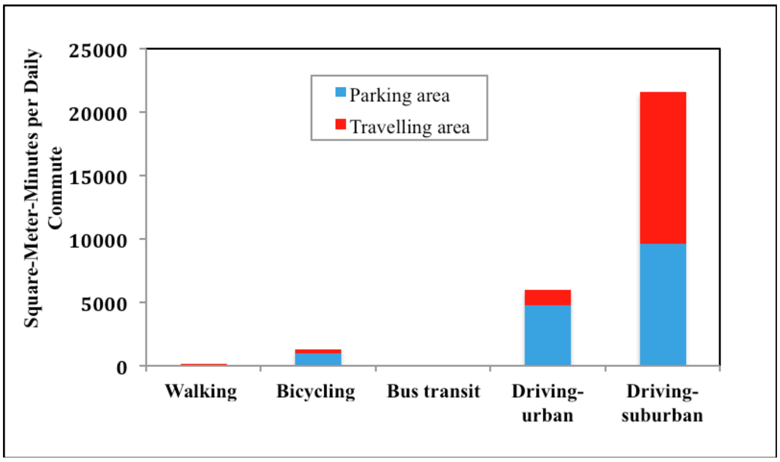


Figure 6. Road and Parking Space Required by Travel Mode. (Source: Kodukula ([113], p. 5). Note: The Figure represents road and parking space requirements for a 20-min commute by various modes of transport, measured in square-meter-minutes (m^2 times number of minutes). Transport modes used in the analysis are: (1) Pedestrian-5 km/h (2) Bicycle-15 km/h (3) Bus-25 km/h (4) Automobile 30 km/h (5) Automobile-100 km/h (Kodukula, [113])).

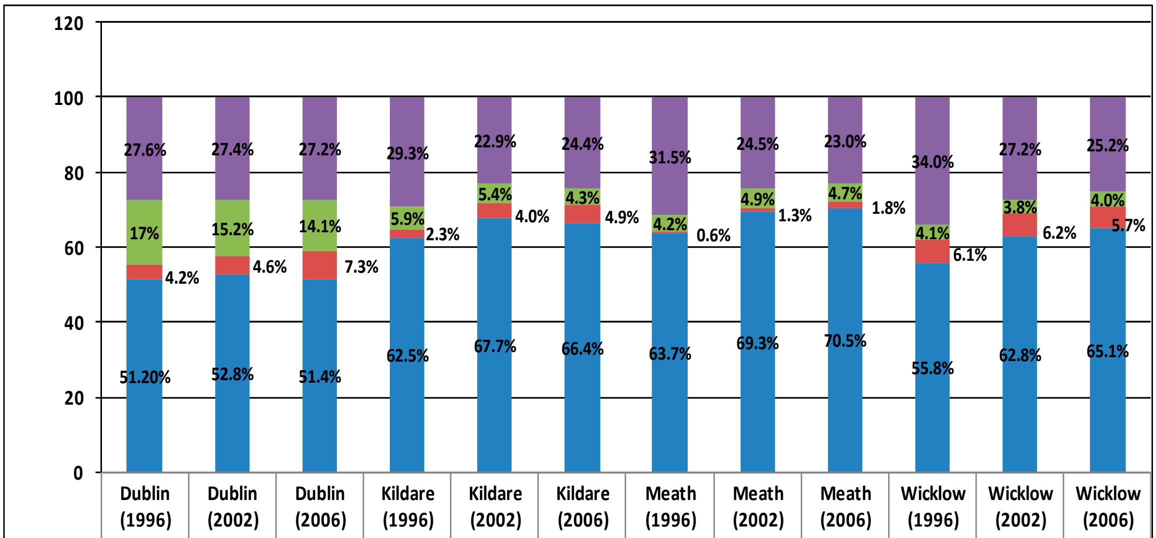
Table 8 shows the surface area per capita for the vehicles, roads and parking spaces and housing footprints linked with alternative development patterns of compact, sprawled and mixed land-use developments (see Litman [111]). It can be followed from Table 8 that compact development requires less than half as much land for housing, roads and parking facilities compared to sprawled development. This implies that compact and transit-oriented development policies can reduce land and energy consumption and number of private vehicles and the associated costs.

Table 8. Per Capita Surface Area for Alternative Development Patterns.

	Compact Development	Mixed Development	Sprawled Development
Vehicles per capita	0.5	0.65	0.8
Road space per vehicle (sq-ft)	235	453	670
Off-street parking spaces per vehicle	2	4	6
Land area per parking space (sq-ft)	275	300	325
Housing footprint per capita (sq-ft)	250	375	500
Road and parking land area per capita (sq-ft)	878	1344	1811

Source: Litman [111].

Regarding existing transportation patterns in Dublin and the surrounding counties, it can be noted that there is increasing number of car-based trips that is associated with dispersed development patterns that has been observed in the GDR since early 1990s (Figure 7). From Figure 7, there is increasing number of car-based work trips both in Dublin and Mid-East Regions (Kildare, Meath and Wicklow) (see Figure 1) within 1996–2006 periods. The share of private car based trips is overwhelmingly the highest among all work trips, which is followed by other modes of transport, bus and then rail-based trips for both Dublin and some other Mid-East Counties (i.e., Meath). In 2006, the share of private car and bus trips declined in Dublin while the share of rail slightly increased compared to modal shares of work trips in 2002. One reason can be related to the shifts from private car and bus uses to light rail (i.e., Luas network), which commenced operations in 2004 with two existing lines. Another reason is the increase in rail transportation in the Mid-East Region which is the origin of so many commuting trips to Dublin (Figure 1).



	Dublin (1996)	Dublin (2002)	Dublin (2006)	Kildare (1996)	Kildare (2002)	Kildare (2006)	Meath (1996)	Meath (2002)	Meath (2006)	Wicklow (1996)	Wicklow (2002)	Wicklow (2006)
other	27.6	27.4	27.2	29.3	22.9	24.4	31.5	24.5	23.0	34.0	27.2	25.2
bus	17	15.2	14.1	5.9	5.4	4.3	4.2	4.9	4.7	4.1	3.8	4.0
rail	4.2	4.6	7.3	2.3	4.0	4.9	0.6	1.3	1.8	6.1	6.2	5.7
car	51.20	52.8	51.4	62.5	67.7	66.4	63.7	69.3	70.5	55.8	62.8	65.1

Figure 7. Total Trips to Work, 1996, 2002 and 2006, Dublin and Mid-East Counties (Kildare, Meath and Wicklow). (Source: Census 1996, 2002, 2006, CSO [114–116]). Note: The y-axis in the figure shows percentage distribution of different modes of transport (e.g., car, rail, bus, other) in the GDR.

Table 9 also presents the changing pattern of home to work trips in the GDR for the years 2002 and 2006. From this table, there is substantial increase in the rail usage between 2002 and 2006 periods in the GDR prior to an increase in rail-based investments in the area. There are also increases in the usage of other modes of transport i.e., bus, car walking/cycling and others in the same period resulting from increasing travel demand with the subject modes of travel. However, these changes are modest when compared to the changes of total number of work trips associated with the rail-based transport.

These findings indicate that public transit infrastructure investments lead to a shift from private car to alternative modes of transportation including rail, bus, walking and cycling. Therefore, with rail scenario of compact development will result in more use of alternative transportation modes than use of private cars, which leads to savings in vehicle ownership costs, parking costs and costs of land development required for roads and parking spaces (Table 8). The data regarding parking costs, costs for vehicle ownership and land development costs for roads and parking spaces for both with rail and baseline dispersed development scenarios are currently unavailable for the GDR. Through use of an operational transportation model (such as MNTM), trip generation and parking generation rates can be computed, from which local traffic and parking impacts can be derived and impact fees can be set. Future vehicle ownership and the change in road and parking space development between the two scenarios can also be derived from the Transportation Model (e.g., MNTM). The availability of such data will help us to improve our cost-benefit analysis and therefore inclusion of discussed impacts in the CBA is suggested as a future research.

Table 9. Total Number of Work Trips by Means of Travel to Work in the GDR, 2002 and 2006.

Year: 2002					
County of Residence	Means of Travel				
	Bus	Train or DART	Car	Walking/Cycling	Others
Dublin	75,916	22,822	264,192	85,408	28,055
Kildare	3942	2962	49,861	7043	6226
Meath	2869	743	40,369	4521	5751
Wicklow	1807	2934	29,549	5229	4289
GDR Total	84,534	29,461	422,342	102,201	44,321
Year: 2006					
County of Residence	Means of Travel				
	Bus	Train, DART, LUAS	Car	Walking/Cycling	Others
Dublin	79,219	40,810	288,115	93,985	27,624
Kildare	3889	4443	60,149	9114	7577
Meath	3636	1416	54,748	5706	7818
Wicklow	2258	3197	36,673	5476	4908
GDR Total	89,002	49,866	439,685	114,281	47,927
% Change between 2002 and 2006	+5.3%	+69.3%	+6.6%	+11.8%	+8.1%

Source: CSO (2003; 2007).

4.3. Results from Sensitivity Analysis

Followed by the CBA results presented in the previous section, a combined sensitivity testing was carried out by setting some specific parameters which simultaneously influence the appraisal outcomes in contrast to the individual sensitivity testing approach having individual impacts on the outcomes. As a priority, two different economic conditions were represented through the parameters including economic growth and recessionary development (as it is the focus of the scenario analysis). These parameters utilised in economic growth and prolonged recession scenarios are summarised in Table 10.

Recessionary Development Cases

As shown in the table, Economic Growth (EG)-Case A represents a simultaneous change in the parameters with no estimation bias in the capital expenditures while EG-Case B involves a 40% capital expenditure uplift. In a similar vein, Recessionary Development (RD)-Case A represents a change in all parameters as given in Table 10 indicating no estimation bias in capital expenditures. In contrast, there is a 40% uplift representing the correction of the bias in capital cost estimations in the RD-Case B.

ENPV for the EG and RD scenarios was sensitivity tested to the original ENPV estimates given in Table 4. Figure 8 presents the results which indicate a considerably high sensitivity across all the discount rates, in particular the sensitivity is the highest with a discount rate of 3%. From this figure, EG-Case A improves the ENPV in a positive direction showing a maximum change of 504% in the ENPV with a minimum change of 46%, the former discounted at 3% and the latter at 5%. RD-Case A also changes the ENPV in a positive direction, however the corresponding curve is below the EG-Case A showing the impacts of prolonged recession on the CBA outcomes when compared to the economic growth results presented by the curve EG-Case A.

Table 10. A Combined Sensitivity Analysis: Simultaneously Set Parameters in Economic Growth and Recessionary Development Cases.

Factors/Impacts subject to Sensitivity Testing	Parameters in Economic Growth (EG)-Links to Business-As-Usual and with Rail (Economic Growth Case) Scenarios	Parameters in Recessionary Development (RD)-Links to Business-As-Usual and with Rail (Prolonged Recession Case) Scenarios
Capital Expenditure Uplifts	EG-Case A: No capital estimation bias EG-Case B: −40% bias in capital estimation	RD-Case A: No capital estimation bias RD-Case B: −40% bias in capital estimation
Value of Time	World Recovery Scenario $E_{Inter\text{-}temporal} = 1.0$ $E_{VTTS,Income} = 1.0$	Prolonged Recession Scenario $E_{Inter\text{-}temporal} = 0.7$ $E_{VTTS,Income} = 0.7$
Accident Costs	World Recovery Scenario	Prolonged Recession Scenario
Road Vehicle Operation Costs	Moderate Price Scenario	High Price Scenario
Metro Operation Costs & Revenues	World Recovery Scenario	Prolonged Recession Scenario
School Transportation Costs	World Recovery Scenario High Growth Scenario	Prolonged Recession Scenario Low Growth Scenario
Electricity Connection & Distribution Costs	World Recovery Scenario High Growth Scenario	Prolonged Recession Scenario Low Growth Scenario
Climate Change	Higher CO_2 Values compared to Central Values	Lower CO_2 Values compared to Central Values
Local Air Pollution	World Recovery Scenario High Growth Scenario $E_{LAP,Income} = 1.0$	Prolonged Recession Scenario Low Growth Scenario $E_{LAP,Income} = 0.7$
Commencement Period of Metro Construction	2013	2013
Appraisal Period	2011–2047	2011–2047

Notes: $E_{Inter\text{-}temporal}$: inter-temporal elasticity to GDP per capita growth representing the variations in value of travel time savings over time, $E_{VTTS,Income}$: the cross-sectional elasticity to income representing the variations in value of travel time savings (VTTS) according to income variations, $E_{LAP,Income}$: income elasticity of demand showing the differences in the value of local air pollution (LAP).

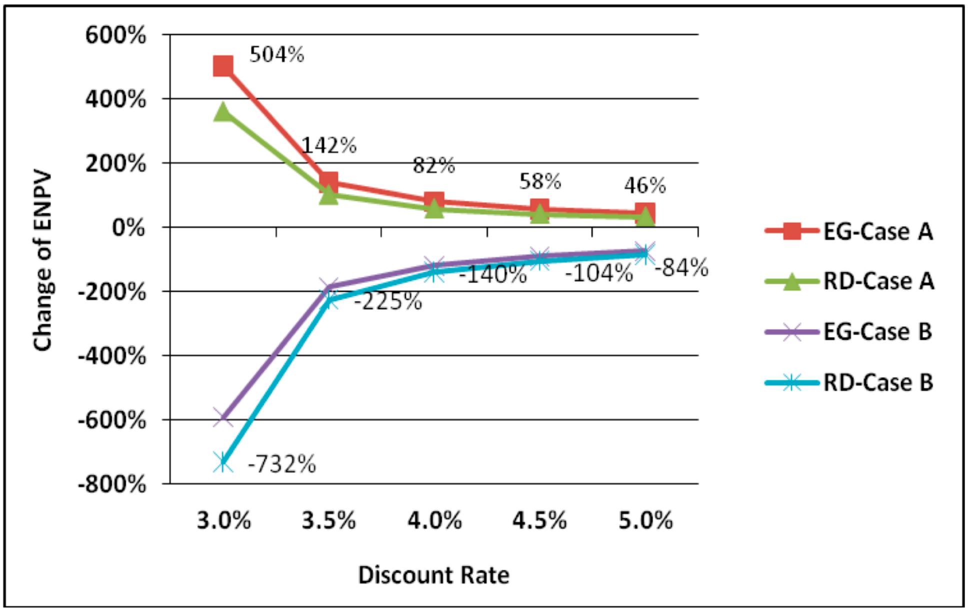


Figure 8. A Combined Sensitivity Analysis: Change in the ENPV compared to Economic Growth Case A–B and Recessionary Development Case A–B.

5. Conclusions

In this research, the sustainability implications of transportation and land-use relationships have been addressed by identifying and evaluating the key linkages and impacts of transportation infrastructure provisions on land development trends in the GDR. The integration of scenario analysis provides an improvement to the existing cost-benefit evaluation framework as it allows the consideration of urban form and development be incorporated in the analysis. In this context, three different land development scenarios were prioritised and developed including a baseline business-as-usual scenario and two alternatives with rail scenarios. The identification and prioritisation of these different land development scenarios can allow the CBA process to be used as a policy support tool in discussions of alternative development and investment decisions such as compact and dispersed developments both in the GDR and some other urban areas of interest.

A review of the literature on the sustainability of transportation-land-use relationships highlights the existence of a growing need for an evidence-based policy making approach concerning major transportation projects and programs. This approach is essential for public transportation proposals especially rail-based transportation considering its long-term impacts on urban form and development. Rapid rail infrastructure investments such as metro-based systems are highly expensive as such investments place significant burdens on government finances. Therefore, alternative scenarios and impact evaluation of rapid rail transport policies and programs is a necessary priority and recommended for contributing to government's budgetary planning and control and assessing wider impacts of such developments on the society.

The CBA findings of this research have confirmed that the expected benefits from an integration of public transportation and multi-centred development in the GDR could probably be achieved in the longer-term implying a time over 40 years or more. The high infrastructure costs of the Metro North investment are identified as the main factor extending the time for receiving benefits from this process. The cost issue emerged as the principal concern following our initial CBA findings. The existing urban structure and incomplete urban transformation processes in the GDR [117] from a traditional compact city into a polycentric urban structure is also significant. This transformation implies a more complicated trip pattern with an increase in the number of trips, trip distances and travel time between a number of sub-centres and a strong CBD.

The integration of the Metro North with other rail-based provisions of the Transport 21 program improves the benefits achieved from the metro investment in the long-term as this was confirmed by the CBA results. A further implication of this result suggests that a comprehensive integration of the rail-based transportation and land-use planning in the GDR is likely to achieve a more pronounced decentralised urban form with a reduction in continuing dependency on a strong CBD in the Dublin area. This future urban form can possibly involve a number of mixed-use and densely developed sub-centres which will improve the benefits expected from a decentralised urban form. These benefits are unlikely to be achieved in the medium-term as the evidence from our CBA findings show that the transformation can still be in progress for the coming 35 years or more.

Further to these findings, the problems with the data and the existing bias with some of the indicators have been underlined throughout the study to emphasise their impacts on the CBA outcomes which in turn affects policy and decision-making actions. Therefore, it can be expected that the correction of the subject problems and bias in indicators will improve the CBA outcomes considerably as we have found evidence for this while carrying out a combined sensitivity analysis for both economic growth and recessionary development scenarios. Based on these corrected findings, with rail scenario of economic growth is favoured in the medium-term depending on the use of specific lower discount rates and consequent costs (either 3% or 3.5%) in the analysis. In the present study, combined sensitivity analysis has been done by focusing on two different economic development scenarios i.e., with rail scenarios of both economic growth and recessionary development compared to the baseline business-as-usual case. Therefore, by developing scenario analysis, the current study was able to present the distribution of land uses varying across the scenarios by using the relevant maps and these maps were compared based on the CBA modelling approach followed by a combined sensitivity analysis based on simultaneous changes in the parameter values. In other words, this study has pointed out that the outcomes of such a CBA process can be mapped and compared on spatial configurations as well as on monetary basis. These proposed linkages between spatial mapping and a CBA approach comprising a combined sensitivity testing of the scenarios can be accepted as a pronounced improvement on the ongoing CBA modelling work both in Ireland and in the international research.

Some possibilities of future developments were considered in this study such as timings of economic recovery or prolonged recession using scenario analysis. It has been shown that unexpected changes in the economy have significant impacts on the urban structure of the GDR. The probable outcomes in urban development shown using the with rail scenario of economic growth and with rail scenario of prolonged recession have indicated differences in appraisal outcomes from the CBA model. Unexpected fluctuations in external factors influence urban structure and development and affect the benefits and costs received by the society. This research underlines the importance of flexible planning tools and policies as well as co-ordination and integration in infrastructure, economic development and land-use planning activities to coincide with uncertainties in future developments. In this regard, a comprehensive evaluation of planning system and the structure of planning institutions in Ireland as they relate to transport infrastructure provision and investment is important as a future research focus.

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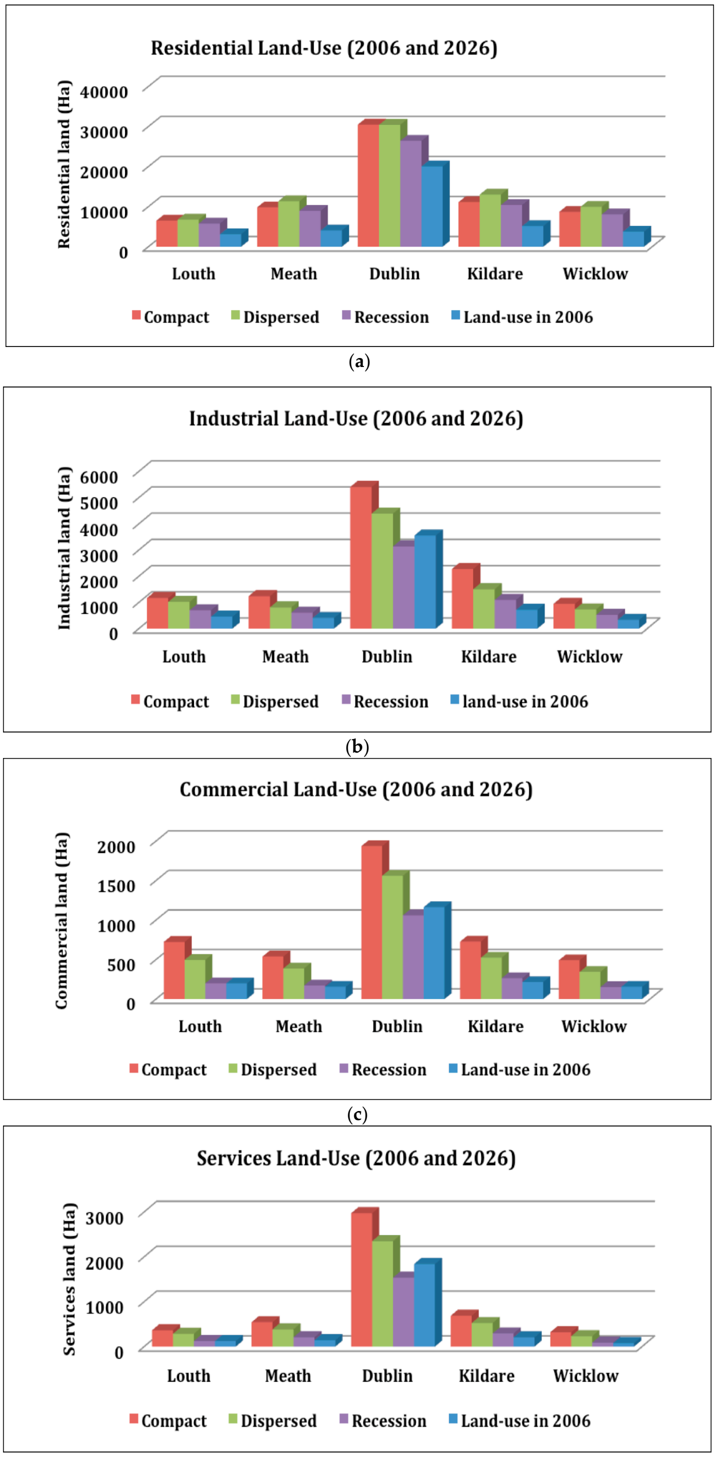
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



(d)

Figure A1. Comparison of Residential, Industrial, Commercial and Services Land in the Counties by Scenario (2006; 2026). (**a**) Change in residential land-use across the scenarios from 2006 to 2026; (**b**) Change in industrial land-use across the scenarios from 2006 to 2026; (**c**) Change in commercial land-use across the scenarios from 2006 to 2026; (**d**) Change in services land-use across the scenarios from 2006 to 2026.

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