Radiological dispersal events within urban environments: A general method of measuring the economic impacts

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ABSTRACT

A radiological dispersal device (or dirty bomb) is an affordable, feasible, and economically devastating option for terrorists. By using an input-output modeling technique, the authors present a general method to assess economic impacts resulting from the use of such a device that will aid researchers, government planners, officials, and key stakeholders. The authors extended previous efforts that focused only on direct effects, exploring the indirect and induced effects as well. In applying the method to the case of a mid-sized city, the authors quantified the area within the city with the largest impact, the central business district. More specifically, the detonation of a dirty bomb in this city's central business district would cost approximately $1.4 billion and impact 860 firms in 270 distinct industries. In addition, approximately 18,000 people would be unemployed immediately following the attack, with an additional 113,000 people affected by the shift in the local economy as a result of indirect and induced effects.

Key words: cost estimation, radiological dispersal event, level of impact analysis, planning

INTRODUCTION

Grotto,[1] who is with the Center for American Progress, has argued that among the unconventional weapons that terrorists could use in an attack within the United States, a "radiological weapon, or 'dirty bomb,' is the most likely." Government officials have reinforced the feasibility of this sentiment in a document distributed to the Congress, highlighting a radiological dispersal event (RDE) as one of 15 viable threats that the government must be prepared to confront.[2,*] Moreover, incidents over the last several years have supported these predictions. In May 2003, the US police arrested an American, Jose Padilla, in Chicago's O'Hare airport for his involvement with Al Qaeda in planning a radiological attack on the United States. In January 2003, British officials found documents in Herat, Afghanistan, indicating that Al Qaeda had successfully built a small radiological explosive device and that they possessed training manuals on how to employ it.[3] The failed attempt, in April 2010, to deliver a conventional car bomb in New York's Times Square highlights these risks even further.[4]

An RDE may be the result of a radiological dispersal device (RDD), commonly termed a "dirty bomb." Generally, an RDD is a low-yield conventional bomb surrounded by radiological material such as cesium-137 or cobalt-60. On detonation, the blast of the conventional explosive is designed to spread radioactive material over a wide area where it can be

*The US Department of Homeland Security developed the National Planning Scenarios,[2] a strategic planning document outlining 15 key threat scenarios. Scenario 11 considered an attack using a radiological dispersal device, estimating 180 fatalities, 270 injuries, and 20,000 instances of contamination, resulting in 10,000 people being evacuated to shelters with an additional 25,000 people being ordered to shelter in place. The best estimate analysts derived for the economic impact were simply "up to billions of dollars."

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inhaled or ingested by people, or otherwise absorbed into the environment. Terrorist groups have expressed an interest in using RDDs because they may be potentially devastating economically and psychologically. They are also quite feasible, as the radioactive materials included in RDDs can be stolen or acquired cheaply from the millions of radioactive sources used worldwide in industry, medical applications, and academic research.[5] The US Nuclear Regulatory Commission has, in fact, estimated that within the United States, radioactive material is lost, abandoned, or stolen every day of the year.[6]

Smith et al.[7] have provided an integrated approach that can be used to guide stakeholders as they plan and prepare for any RDE, called a level of impact analysis. Synthesizing several approaches to general risk assessments (eg, Ecological Risk Assessment and Human Health Risk Assessment), Smith et al.'s approach is designed to help assess the impact of an RDE and future risks to ensure efficient recovery. Largely qualitative, the level of impact analysis focuses on the critical factors agreed on by the stakeholders, namely, an economic parameter (representing the economic disruption the event may have on the regional or subregional economy), an ecological parameter (representing the degradation of or impact on a defined ecological receptor or services), a social impact parameter (representing the impact the adverse event has on the quality of life in the subregion), a human health risk parameter (representing the actual risk to human health as a result of insult from radioactive material), and a cost of remediation parameter (representing an estimate of remediation costs).

In this article, we further explicate one element of the level of impact analysis,[7] the economic parameter. More specifically, we present a general method that can be used to assess estimate economic impacts resulting from an RDE, occurring in any location and affecting any industry. By fulfilling this objective, we make several theoretical and practical contributions. Theoretically, our work fills a gap in the literature as there is neither a universal approach for measuring the costs or economic impacts on businesses nor a common framework for estimating economic impacts of a radiological event triggered by a dirty bomb, with this gap leading to inaccurate and unverifiable estimates.

Practically, a general model of assessing costs should improve RDE response efforts by providing government officials and key stakeholders an economic assessment tool that can be used to quantify the economic impacts, thereby facilitating the strategic decision-making process. For instance, local interactions with the Federal Emergency Management Agency (FEMA), the federal government's most visible branch of emergency managers, would be improved as FEMA would be involved once the President declares a disaster in the affected regions. This declaration enables special funding to be allocated to defer the costs incurred by private sector individuals and organizations (ie, federal assistance to households, individuals, and businesses) as well as public sector organizations.[†] To obtain this funding, however, cost estimates must be conducted in the immediate aftermath of a disaster to determine the extent of damage and the costs incurred by public sector organizations' response. Moreover, federal guidelines call for estimates that are accurate to 10 percent within 90 days after the declaration of disaster.[8]

While our manuscript offers a tool that focuses on estimating costs incurred by the private sector, we feel this method could also be used by public sector agencies like FEMA. Currently, FEMA estimates and submits a budget request to have these funds available for a particular fiscal year in the preceding fiscal year as part of the congressional appropriations process. FEMA uses the 5-year annual average level of obligations for past disasters, adjusted for inflation, as its estimate of the total cost of disasters anticipated to occur during the current fiscal year. To estimate when

[†]The President is granted this authority under the Stafford Act. Through this act, cities and states can receive grants to reimburse uninsured extraordinary costs of an emergency response (eg, police and fire department overtime, replace equipment that was damaged or expended in the response, and repair or rebuild affected facilities). In addition, individuals can be given unemployment payments, low-interest loans, and limited grants while businesses may qualify for low-interest loans and limited grant programs designed to recover uninsured losses. Public and private costs are estimated and differentiated during the damage assessment for a Stafford Act declaration, and our article focuses on a technique to estimate the private sector costs—an issue discussed at length in the Discussion section.

these funds are expected to be distributed throughout the year as disasters occur, FEMA simply allows the 5-year annual average to decline at a constant rate (8 percent) each month during the fiscal year. "Using this approach, FEMA estimates that disasters costing about $500 million will occur in August and September 2000. However, these months represent the height of the hurricane season, and over the last 5 years, the average cost for disasters to FEMA has been twice this amount,"[9] and as such, FEMA is regularly underestimating the cost of disaster events, forcing the agency to request additional funds from the Congress. These errors reverberate through the system where funds are shifted from other programs or debt is increased.

ECONOMIC IMPACT OF THE RDE THREAT

The Council on Foreign Relations[10] classifies RDDs as weapons of mass destruction (WMD). Although in the same category as nuclear, biological, or chemical weapons, RDDs are not devices that generate the same widespread destruction and fatalities that are generally linked to other WMD. Although RDDs do lead to destruction and fatalities, the WMD label is applied largely because RDDs are intended to disrupt the normal functioning of society through widespread panic. This is expected to arise from the psychological anxiety that RDDs may trigger based on people's fear and general misunderstanding of radioactive materials. Hospitals, for instance, would likely be overrun with people complaining of and possibly showing symptoms of radiation sickness, even if they were nowhere near an attack site or radioactive fallout. In Brazil, for example, Warwick[11] reported that 249 people were exposed to a radioactive substance, but once the incident became public, 135,000 requested screening for exposure and 5,000 people who were never exposed to the materials showed psychosomatic symptoms of nausea and skin rashes that mimicked symptoms of actual exposure. Warwick argued that false reporting, caused by the anxiety of potential exposure, created significant congestion in the healthcare system and delayed treatment to those who were actually affected.

"The economic impact of a radiological attack has the potential to be as devastating, if not more, than the physical attack itself," according to the Monterey Institute of International Studies Center for Nonproliferation Studies.[12] Although (and quite fortunately) there have been no successful malicious incidents of radiological terrorism using dirty bombs, there have been several notable radiological accidents and terrorist attacks that provide insights into the financial and economic effects a radiological terrorist attack would have. Several specific incidents are summarized in Table 1, highlighting the costs that were associated with each of these incidents. The incidents range from nuclear accidents like the one at Three Mile Island (TMI), Pennsylvania, to the conventional terrorist attacks like the one of September 11, 2001 at the World Trade Centers in the United States.

Generally, these estimates have focused on the direct effects that represent the known or predicted change in the local economy that is attacked. The economic loss associated with the September 11, 2001 attack, for instance, represented a $30.5 billion loss, of which $21.8 billion was the cost to replace buildings, infrastructure, and tenant assets, and $8.7 billion was an estimate of the future earnings of those who died.[13] The TMI accident, by contrast, had an immediate cost of $18 million, as 144,000 people were evacuated within a 15-mile radius of the island.[16] Additionally, the effects on business during the week after the incident were approximately $7.7 million for manufacturing firms and $74.2 million for nonmanufacturing firms.[16,17]

Each of these incidents has also suggested that there would be lingering effects associated with an RDD. The Chernobyl nuclear accident highlighted this point on a grand, national scale. Beyond the $235 billion estimate in costs for Belarus alone,[18] the long-term restrictions on agricultural production crippled the market for foodstuffs and other products from the affected area, resulting in losses from 6 to 22 percent of Belarus' gross domestic product.[18] More inline with what might be seen with an RDD, the citizens of Goiania, Brazil, saw the sales of their cattle, cereals, and agricultural produce fall by 25 percent in the period after an accidental release of a radioactive material.[14,15] In addition, the Gross City Product for Goiania decreased by 20 percent and did not recover

Table 1. Summary of incidents providing economic estimates of conventional and radiological dispersal events				
Event	**Type**	**Description**	**Economic estimates**	**Reference**
September 11, 2001 World Trade Center Attack	Purposeful use of "conventional" (ie, non-nuclear) explosives by terrorists in a large commercial center	A group of hijackers flew fueled passenger jets into each of the World Trade Center buildings, leading to the collapse of each building.	• Infrastructure replacement costs of $21.8 billion • Future earnings of fatalities $8.7 billion • Gross City Product (GCP) loss: $27.3 billion (year immediately following attack)	Thompson[13]
Improper handling of abandoned radioactive medical equipment, Goiania, Brazil (1987)	Accidental release of cesium-137	Two persons entered an abandoned radiation therapy unit after the physician had relocated his practice, taking a piece of medical equipment composed of cesium-137. At home, they dismantled and ruptured the capsule holding the radioactive material. A total of 249 people were externally irradiated, 129 were internally irradiated, and four deaths were caused.	• Infrastructure clean up and replacement costs $27.2 million • Industry sales from the region fell 25 percent after the incident. • GCP loss: 20 percent decrease with no recovery after 5 years.	Warwick[11]; IAEA[14]; Sohier and Hardeman[15]
Release of radioactive material, Three Mile Island Nuclear Generating Station, Pennsylvania (1979)	Accidental release of radioactive noble gases (primarily xenon) and iodine-131	Failures in a non-nuclear secondary system, followed by a pilot-operated relief valve in the primary system that was stuck in an improper configuration led to the release of reactor coolant from a pressurized water reactor. No significant levels of radiation were detected outside of the facility.	• Evacuation costs (144,000 people in 15-mile radius): $18 million • Manufacturing plant losses: $7.7 million • Nonmanufacturing plant losses: $74.2 million • Qualitative costs reported (not captured in monetary terms): Increases in (a) workdays lost, (b) hospital visits, (c) antianxiety medications, and (d) radiation sickness symptoms (although there was no exposure).	Flynn[16]; Walker[17]
Release of radioactive material after explosion at the Chernobyl Nuclear power plant (1986)	Accidental release of an estimated 40 million curies of iodine-131, three million curies of cesium-137, and 50 million curies of radioxenones and radiokryptons	Operators at the Chernobyl nuclear power plant were doing a scheduled low-power engineering test when a succession of human errors coupled with design flaws culminated in a series of explosions, destroying the reactor. Only 31 people died due to the accident directly, whereas 237 people suffered from severe exposure. A total of 330,000 people within a 30-kilometer radius were evacuated, and there have been enduring issues in the area.	• Total cost estimate: $235 billion (Belarus alone) • GDP cost estimates: Range from 6 to 22 percent • Qualitative costs reported (not captured in monetary terms): Lower wages; higher unemployment; and restricted agriculture production	IAEA[18]

(*continued*)

Table 1. Summary of incidents providing economic estimates of conventional and radiological dispersal events (continued)				
Event	**Type**	**Description**	**Economic estimates**	**Reference**
Hypothetical model of an RDD at ports of Los Angeles and Long Beach, California	Simulation of purposeful use of RDD by terrorists at major US ports	Center for Risk and Economic Analysis of Terrorism Events estimated the cost of an RDD being shipped to and detonated on arrival to the ports of Los Angeles and Long Beach.	• Costs of short-term closure (15 days): \$300 million • Costs of mid-term closure (120 period): \$63 billion • Costs of long-term closure (1 year): \$252 billion.	Rosoff and von Winterfeldt[19]
Chechen militants' use of RDDs (1995 and 1998)	Purposeful placement of radioactive material in Moscow's Izmailovsky Park (1995) and the placement of a dirty bomb near a Russian railway line (1998)	• Under Commander Shamil Basayev, militants placed a small quantity of cesium-137, which was thought to be obtained from a nuclear waste storage facility in Moscow's Izmailovsky Park. Although not dispersing the material, the placement of the material created a media storm as a television news crew was directed to the location. • In a second incident, the pro-Russian Chechen Security Service found a dirty bomb consisting of a land mine combined with radioactive materials next to a railway line frequently used to transport Russian troops. Chechen militants were suspected to have placed the device.	• No economic estimates were available.	Burton[20]

to pre-release levels for an additional 5 years. In summary, these estimates suggest that focusing purely on the direct effects may underestimate the costs associated with such an incident.

LeBrun[21] took a key step in developing an approach to predict economic effects beyond the direct effects, capturing the indirect and induced effects as well. The indirect effects represent the business-to-business transactions required to satisfy the direct effect. The induced effect is derived from local spending on goods and services by people working to satisfy the direct and indirect effects. He estimated the total effects that an RDD would have on revenues and employment in the retail center of a mid-sized city based on the relationship between revenue and a retail space's square footage and the Bureau of Labor Statistics (BLS) employment data. He concluded that the total impact of an RDD would be approximately \$1.2 billion (in 2003 dollars), impacting more than 21,000 jobs. In addition, LeBrun[21] suggested that planners should assess the economic impact of an RDE by examining the strategic placement of the device within a metropolitan area. More specifically, he identified three key economic centers within any city that would be attractive targets for an RDE: the business districts, the industrial centers, and the retail areas. Although large urban environments may have numerous districts fitting into each of these categories, he recommended that research focused on the most central of these areas. For instance, the central business district typically contains banks, corporate offices, and service industries such as law firms and accounting agencies and is typically considered the heart of any metropolitan area.

GENERAL ECONOMIC MODEL USING INPUT-OUTPUT MODELING TECHNIQUES

Building on LeBrun's[21] effort and extending the work of those who have examined only direct effects (known changes in the local economy where an incident occurred), we present a model to estimate the indirect effects (ie, costs associated with the business-to-business transactions that would be lost) and induced effects (ie, costs from local spending on goods and services by people working to satisfy the direct and indirect functions) as well. These can be captured using an input-output model. The input-output model is a detailed accounting system of interindustry activities within a local economy and is predicated on the economic theory that the output of one industry often serves the input to other industries.[22] Because of recent improvements in data collection made by the Bureau of Economic Analysis, several governmental and private organizations have suggested that input-output modeling is the most accurate method for measuring the economic impacts of policy changes on a region.[23] Moreover, input-output models have been applied to estimate the economic disruption of other events such as electric power outages,[24] hypothetical earthquakes,[25] and hurricanes.[26]

The Impact Analysis for Planning (IMPLAN)[27] software is one package designed for input-output modeling used to compute the direct, indirect, and induced effects by developing a social accounting system to describe transactions that occur between producers, intermediate customers, and final consumers.[28] It does this through a clear picture of an area's businesses and industries that are described by the researcher and planner. With this data, the IMPLAN input-output modeling program uses an empirically derived social accounting matrix that represents the flows of economic transactions between industries, capturing the indirect and induced effects that result as a "shock" (ie, policy change, natural disaster, or RDD) ripples through the local economy based on the interrelationships among businesses and industries. In addition, IMPLAN derives a multiplier model mathematically, giving it predictive ability in economic impact analysis.[28]

Although the specifics of the software are beyond the scope of this article, the general steps that need to be taken to apply this technique in examining an RDD are summarized in Table 2. These steps include a) identifying key commercial, industry, and retail centers within a city; b) determining the specific businesses that will be influenced by overlaying the impact area on a map; and c) gathering economic and employment data for the area from the BLS. Finally, the data can be analyzed and the lost revenues and employment can be estimated, testing how different economies of scale influence the area as well as capturing the specific seasonal effects.

Consistent with the planning process laid out by Smith et al.,[7] the first step in the method is locating the distinct sites within the metropolitan area that would be attractive targets. Smith et al.[7] suggested that vulnerability assessments should aid in the identification of the most attractive target areas from a terrorist's perspective. With that said, planners can use a basic understanding of terrorists and their motivations to guide planning. Terrorist acts are typically prompted by psychological, political, religious, cultural, or economic motivations,[32] and terrorists prefer that their operations be executed in highly visible, public areas that dramatically influence a region.[33] As such, LeBrun[21] has persuasively argued that the key targets for an RDE are an area's central business district, its industrial center, and its retail center.

In the second step, stakeholders must determine what commerce would be affected in the target areas. The Department of Homeland Security's National Planning Scenario[2] offers considerable guidance as this is done. Specifically, it indicates that nearly all of the fallout from an RDD would likely be contained within a 1-mile diameter zone centered on the detonation site. With this, planners can simply overlay concentric circles onto an aerial photomap of the central business district, industrial center, and retail centers to provide a clear picture as to which businesses within a particular region would be directly affected with contamination. Partnering with the BLS, which compiles data by zip code, the specific businesses within an affected area can be identified and refined to a specific area (ie, a 1-mile diameter around a specific detonation site). These firms must be organized into industry-specific

Table 2. Economic modeling steps

Modeling step	Issues to consider and actions taken
Identification of attractive target areas	Leaders should conduct or rely on formal vulnerability assessments to identify the most attractive target areas from a terrorist's perspective. As a general guide, leaders should identify the following: • Key commercial centers to include the metropolitan areas central business district. • Key industrial centers that employ significant numbers of employees and have several complementary industries collocated within a mile. • Key retail areas that have considerable service providers and have considerable traffic of patrons.
Identification of the specific businesses within a particular target area	Leaders should rely on the Department of Homeland's scenario that describes an RDD to guide the identification of businesses. Thus, leaders should consider the following: • 97 percent of fallout is expected to be within a 1-mile diameter of the detonation site. • Weather conditions are calm (ie, light winds of 3-8 mph) and there is no precipitation, allowing an initial estimation to be circular around the detonation site. • All businesses within the 1-mile diameter will be closed for an extended duration. With this, leaders can (a) overlay a circle (or concentric circles to estimate areas of decreasing impact and compute various estimates) onto an aerial map to highlight impacted areas; (b) identify affected zip codes; (c) forward this information to the Bureau of Labor Statistics (BLS) to identify specific businesses; and (d) recode these businesses according to their North American Industrial Classification System (NAICS) codes (which is necessary for input-output modeling.
Collection of economic and employment data within a particular target area	Leaders should focus on revenues and employment as these numbers are the key measures of economic impact and can be easily obtained by partnering with the BLS. In addition, leaders should consider the following sources. • US Census Bureau 2007 Economic Census[29] • County Business Patterns (2007)[30] • American Fact Finder: Economic Patterns[31]
Scale the data to reflect a specific region in a metropolitan area and capture economies of scale	Leaders should test two distinct functions: a constant economy of scale function and a linear economy of scale function. The constant economy of scale function provides a simple baseline. Under the linear economy of scale function, employees in larger firms produce more revenue than their counterparts in smaller firms. The constant economy of scale baseline can be developed based on ratio of employees in each size category to total employees within a given industry. This allows the distribution of the annual revenue based on the given weights revealing approximate annual revenue based on categorized firm sizes for each industry. With this, a weight is developed based on the specific site to be tested. This scale used the ratio of employees in a given category at the site-specific level to the number of employees for the same industry and size category for the metropolitan area.*
Test the seasonal affects associated with an RDD for a particular target area	Leaders should consider the timing of the RDD. Monthly revenue data are published and can be used to compute a total effect by month. Then, seasonal effects can be identified by taking the difference between the cumulative seasonal effects from the cumulative nonseasonal impact.

*To compute this linear function and calculate revenues, two integrals are computed: Total revenue = $\int_1^n mx(dx)$; Weight = $\int_a^b mx(dx) / \int_1^n mx(dx)$; n = number of employees in an industry; a = 1+ number of employees in ALL previous size categories; b = number of employees in a size category + number in ALL previous size categories.

groups using the North American Industrial Classification System (NAICS).‡

With the affected businesses identified and grouped in the NAICS categories, the economic parameters necessary to calculate the economic impacts should be defined. For most cases, annual revenues and employment data would be recommended. These data can be collected from the BLS or a number of other sources, namely, the US Census Bureau 2007 Economic Census[34]; *County Business Patterns* (2007 data were published in 2009)[29]; and American Fact Finder: Economic Patterns.[30] The BLS can further refine the data to the six-level NAICS identifier because data collected from online sources will be masked at such a high level of fidelity and would need to be unmasked (which can be done on special request without identifying individual firms).

Revenue data may only be available at the level of the metropolitan area rather than a more specific area (ie, a specific business district, industrial center, or retail center). Thus, these data would need to be scaled to estimate revenue generated within a more particular area. This scaling can be conducted in several ways, but it is suggested that two distinct functions be tested: (a) a constant economy of scale function and (b) a linear economy of scale function (which is used for sensitivity analysis in the subsequent step). Briefly, economies of scale are the cost advantages that a business obtains as it expands (ie, increases its scale) by decreasing the average cost per unit produced. The most common advantages a firm may experience by increasing its scale are as follows: purchasing (ie, bulk-buying of materials through long-term contracts), managerial (ie, increasing the efficiency through the specialization of managers), financial (ie, obtaining lower interest charges when borrowing from banks and having access to a greater range of financial instruments), and marketing (ie, spreading the cost of advertising over a greater range of output in media markets). The constant economy of scale function provides a baseline under the assumption that an employee in a given industry produces the same revenue as any other employee in that industry.

Although economies of scale vary from linear to exponential functions depending on the individual firm and industry,[31] a linear economy of scale function can begin to capture the dynamic environment in which employees in larger firms tend to produce more revenue than their counterparts in smaller firms. By varying economies of scale between 1 and 100 percent, a range of the impacts can be determined, providing a key sensitivity analysis. From this analysis, ranges of the expected effect can be computed. This provides civic leaders using the current model with an estimate of the range of damage that would emerge.

Finally, the timing of the RDD is critical and should be considered as the economic impacts are assessed. A retail center in the United States, for instance, typically makes most of its revenue in October, November, and December. A detonation of an RDD during the fall months would likely increase the economic impact of the RDE by disrupting business during the peak, revenue producing months. To model seasonality, monthly industry revenue data can be used and monthly percentages can be computed for each industry in a particular area. To determine which month results in the largest economic impact, the seasonal effects must be isolated from the total effects by differentiating the cumulative seasonal effects from the cumulative nonseasonal impact. To demonstrate the model, we examined the effect of an RDD on a mid-sized (population ~500,000) city in the Midwest surrounded by crop land and located in a watershed, near the source of the city's drinking water.

APPLICATION OF THE MODEL: THE CASE OF A MIDWESTERN CITY

The city chosen to demonstrate the model represents an appropriate application because it has several business districts, industrial centers, and retail centers. The particular business, industry, and retail centers examined represent the largest of their types in the entire metropolitan area, giving decision makers the worst-case scenario. The business district chosen has

‡This is important as IMPLAN analyzes impacts on individual industries, not individual businesses. NAICS groupings are the standard used by federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the economy. Moreover, IMPLAN further consolidates these industries into sectors, examining 509 different economic sectors.

approximately 15 percent of the metropolitan area's business firms and accounts for nearly 12.5 percent of the metropolitan area's revenue. When compared with the area's three other major business centers, the business district chosen produces 50 percent more revenue on average. The industrial center chosen includes a large vehicle assembly plant but contains only 3 percent of the area's industrial firms. Still, it accounts for 18.4 percent of the revenue from the metropolitan area's industrial sector; also, it makes on average 67 percent more revenue than four other industrial areas within this particular metropolitan area. The retail center contains 8 percent of the metropolitan area's retail firms, accounts for 17.84 percent of the total revenue in this sector with an average of nearly 30 percent more revenues than other area retail centers.

The incident considered was consistent with the Department of Homeland Security's National Planning Scenario.[2] As noted, this scenario suggests that 97 percent of the fallout of the radioactive material would fall within a 36-block or 1-mile (diameter) area; 90 percent of the radiation source would be aerosolized and carried by winds, with radioactive particles ranging in size from 1 to 150 μm. The remaining fallout would create debris and contaminate surrounding structures. Accordingly, businesses within the 1-mile area would be closed for an extended duration while contamination would be remediated. Moreover, we assumed that there was no precipitation with light, variable winds of 5 to 13 km/h (3-8 mph), and the temperature is 18°C (65°F).[§] The RDD was assumed to contain cesium (Cs-137; 2,300 curies), because this radioactive isotope is one of two (cobalt-60 being the other) elements most commonly used within industrial and commercial radioactive sources. Although the most hazardous radioactive materials are found in nuclear power plants and sites where nuclear weapons are made, experts argue that these are extremely difficult (although not impossible) to obtain because security at these locations is high. Thus, the most likely radioactive materials in RDDs would be cesium or cobalt that come from low-level waste generated through medical laboratories (eg, diagnostic procedures and cancer treatments) or welding shops and construction sites (eg, industrial radiography).[19]

As outlined in our process, the detonation site was centered to include as many firms in each area as possible. The scenario described was overlaid on a map such that specific businesses could be identified and coded in accordance with the NAICS. Then, the annual revenue and employment data were easily collected. For this example, revenue and employment data was obtained from the 2007 Economic Census; the BLS assisted in unmasking the data that had not been divulged previously to prevent individual firms from being identified. Once the data were unmasked, the revenue data were scaled for each industry to reflect the actual composition of industries in the central business district, the industrial area, and the retail center. The direct, indirect, and induced effects on revenues and employment for each of these areas over a 1-year period, while holding economies of scale constant, are summarized in Table 3. Given these parameters, it was no surprise to see that the direct, indirect, and induced estimates vary based on the location where the RDD was detonated within the city, namely, the central business district, the industrial area, or the retail center. Still, the proportions of costs attributed to direct, indirect, and induced effects remained consistent independent of the particular site (ie, business, industry, or retail) with approximately 60 percent coming from direct costs, 15 percent from indirect costs, and 25 percent from induced costs.

In this particular city, the central business district was, without any doubt, the area that would be most affected economically by an RDD. This was not unexpected as the central business district is at the heart of many metropolitan areas, containing the largest number of firms that generate significant revenues. It might be reasonable to expect that a disruption in the central business district of most metropolitan areas would yield the greatest impact.[35] In this particular city, the total annual economic impact would be expected to be approximately $1.4 billion (with a

[§]To make estimates more robust, more specific weather conditions can be estimated as these weather conditions change the shape and size of the contamination area. With our assumption of good weather, the distribution of contamination would be circular.

Table 3. Direct, indirect, induced, and total effects on revenues and employment for the case of a mid-sized city								
	Impact on revenue (LB based on 1 percent EoS, UB based on 100 percent EoS)				Impact on employment			
	Direct effect	Indirect effect	Induced effect	Total effect	Direct effect	Indirect effect	Induced effect	Total effect
Central Business District (affecting 860 businesses)	$840.1 ($812.8, $883.9)	$250.8 ($244.9, $260.9)	$327.2 ($315.2, $345.6)	$1.42 billion ($1.37 billion, $1.49 billion)	18,137	46,020	66,837	130,994
Industrial Center (affecting 580 businesses)	$696.5 ($683.8, $710.4)	$168.4 ($166.5, $170.2)	$236.4 ($232.0, $242.0)	$1.1 billion ($1.08 billion, $1.12 billion)	20,248	43,737	55,167	119,152
Retail Center (affecting 575 businesses)	$522.1 ($498.2, $538.8)	$137.8 ($131.1, $142.4)	$231.1 ($221.1, $238.2)	$891.0 ($850.4, $919.4)	12,156	28,143	46,562	86,861

Note: All values in millions unless noted.
Abbreviations: LB, lower bound; EoS, economy of scale varied linearly; UB, upper bound.

range of ±$101.3 million), affecting approximately 18,000 people directly and another 113,000 from indirect and induced effects. In addition, the central business district in this city contained numerous public buildings such as courthouses and the city hall. Moreover, it had high vehicular and pedestrian traffic and contained the central node to the public transportation system that allowed low-income individuals who did not have vehicles of their own to access the city suburbs, having significant induced affects.

There were considerable economic impacts if an RDD were detonated in the industry and retail centers as well. The total annual economic impact in the industrial center would be approximately $1.1 billion (where direct costs were $696 million, indirect costs were $168 million, and induced costs were $236 million), affecting approximately 20,000 people directly and another 99,000 from indirect and induced effects. A detonation in the retail center would cost approximately $891 million (where direct costs were $522 million, indirect costs were $138 million, and induced costs were $231 million). In terms of jobs, about 12,000 individuals would be affected directly and nearly another 75,000 would be affected through indirect and induced effects.

Sensitivity analysis

By accounting for how much more revenue large firms typically generate when compared with smaller firms (ie, varying economies of scale), it was possible to develop a range of effects and ensure the model was capturing variation as it should and give policy makers a range of costs. As such, we varied the economies of scale linearly from 1 to 100 percent. Our analysis indicated that the most variation in the costs were within the central business district. The direct effects of an RDD would seem to vary the most with a minimum cost estimate of $812.8 million (when the economies of scale were 1 percent) to $883.9 million (when the economies of scale were 100 percent). Indirect costs ranged from $244.9 to $260.9 million while the induced costs varied from $315.2 to $345.6 million. Moreover, we observed that as a larger firm's employees produced more revenues (ie, economies of scale approached 100 percent more revenue per employee for a larger firm), the effects were magnified. This was expected because the central business district had numerous firms of varying size that were collocated and vying for the same business (ie, several accounting firms competing for the same customers). As the economies of scale are varied, the range of costs would vary accordingly.

In contrast, the least variance was observed in the industrial center as most of the businesses collocated in this area were complementary (eg, a brake manufacturing plant produced a product in support of or in conjunction with a vehicle assembly plant) and the firms tended to be of similar size. Moreover, the smaller firms that were located in this area were generally not competitors and were instead services dependent on the main industry (eg, restaurants, barber shops, or gas stations). The direct effects of an RDD would seem to vary the most with a minimum cost estimate of $683.8 million (when the economies of scale were 1 percent) to $710.4 million (when the economies of scale were 100 percent). Indirect costs ranged from $166.5 to $170.2 million, whereas the induced costs varied from $232.0 to $242.0 million.

Although the variation in the retail center would not be expected to be as great as that observed in the central business district, it would be expected to be greater than the industrial center. The retail center was made up of an interesting combination of competing (eg, large department stores) and complementary businesses (eg, food and spa services). In addition, the size of the firms competing with one another was largely the same (eg, one anchor store of a mall does not typically vary dramatically in size when compared with another). Still, the direct effects would seem to vary the most with a minimum cost estimate of $498.2 million (when the economies of scale were 1 percent) to $538.8 million (when the economies of scale were 100 percent). Indirect costs ranged from $131.1 to $142.2 million, whereas the induced costs varied from $221.1 to $238.2 million.

Seasonality analysis

Finally, we analyzed the seasonal effects of an RDD in this region. Perhaps naively, we originally assumed that an attack in October, as this would influence the retail businesses the most dramatically, would be the most costly for all areas. Yet, the analysis indicated that an attack in the summer months would result in the largest economic impact for the central business district and the industrial center. Specifically, an RDD detonated in the central business district in June would result in an additional $6.7 million in economic losses above the cumulative (nonseasonal) average. Conversely, an attack in December would net $9.4 million below the cumulative average. Similarly, the summer months would be most costly to this city's industrial center with a July attack leading to a cost of $14 million above the nonseasonal average, whereas a December attack would result in an impact $12 million below average.

The retail center did reveal the findings we expected. An RDD detonation in October at the start of the peak period of consumer purchases, which typically occur from October to December, would most dramatically disrupt this area. Our data supported this, showing an October attack would have $51 million effect above the average. An attack in January, immediately after the peak season, would have effects $70 million below the nonseasonal average.

DISCUSSION

Smith et al.[7] offered a streamlined, adaptive planning approach that should be used by key stakeholders as they plan and prepare for an RDE. One critical element that they suggest to be considered through the planning and deliberations are the economic costs. Kelly[36] also argued that the reliance on "no cost limit" emergency appropriations after an event can contribute to dysfunctional recovery strategies and inefficient responses. Accordingly, we present a repeatable method that can be used in any metropolitan area to estimate the impact of an RDE. This process entails (a) the identification of key target areas, which are likely the commercial, industry, and retail centers within a city; (b) the identification of specific businesses that will be influenced by overlaying the impact area on a map using the Department of Homeland Security's guidance regarding an RDD; (c) the collection of economic and employment data from the BLS; (d) the analysis of the data with an input-output modeling software package like IMPLAN (another program is RIMS II from the Bureau of Economic Analysis; ref. 37); and (e) the exploration of the model's sensitivity (ie, examining different economies of scale) and the seasonal effects.

This general approach offers several advantages. By applying this method, planners are able to estimate the indirect and induced effects as well as the direct effects, which would be an improvement over other estimates as these costs account for a substantial economic impact. An input-output modeling technique captures direct, indirect, and induced effects for any given industry in any given location by accounting for the relationships among industries in the specified geographical area. In addition, our method can more effectively account for the dynamic and complex nature of the event despite the fact that it is based on historical economic data. This is because it can be updated relatively easily to reflect the changing industry composition within a particular region and account for changing economic conditions as the BLS continually publishes updated data regarding a region. Finally, leaders can get a "worst-case scenario" by initially identifying and estimating the impacts to the largest (by overall revenue generated) commercial, industrial, and retail districts within a particular metropolitan area. To further account for uncertainty and improve the estimate for planners, a range of predicted costs can be estimated by taking the economies of scale into account and examining the seasonal effects on the region.

As we applied this method to evaluate the costs of a scenario suggested by the Department of Homeland Security[2] on one mid-sized Midwestern city, we found the effects of an RDD to be devastating. The most substantial impact would occur if an RDD were detonated within this city's central business district. Such an attack would result in a total effect of $1.4 billion over a 1-year period and an attack during the summer months of June, July, and August would produce the greatest seasonal costs. Additional factors would also magnify the effect of an attack on a city's central business district. This area typically includes transportation and decision-making (like city hall) nodes hampering coordination among fire, police, and medical responders, disrupting citywide traffic flow, and restricting the movements of residents as well as goods and services. Still, our analysis of a particular city indicated that attacks on an industrial and retail center should not be discounted, as they would have a 1-year total effect of $1.1 billion and $900 million, respectively.

We also found that the direct, indirect, and induced costs represented approximately the same proportion of the total costs regardless of the detonation site (ie, central business district, industrial center, or retail center). That is, the direct, indirect, and induced costs represented approximately 60, 15, and 25 percent of the total costs, respectively. This is significant for several reasons. First, this improves previous estimates that have focused only on the direct effects and may have overlooked key factors in the total costs associated with an RDD. Second, this information should help planners to more accurately quantify a well-understood phenommena, namely, there are time-lagging effects to any disaster. In the case of an RDD, our data suggest that nearly 40 percent of the economic effects will be realized months after the RDD. When these are not considered, the effects are broadly underestimated that has considerable policy ramifications at all levels of government. FEMA, for instance, has routinely underestimated the cost of disaster events by nearly half (which is consistent with our results), forcing the agency to request additional funds from the Congress.[10] As we have noted, additional requests reverberate through the government's system where funds are shifted from other programs or debt is increased. Thus, improved cost estimates of events can improve the efficiency and effectiveness of the entire system.

Although not the focus of our effort, we also noted a relationship between the estimated economic impact of an RDE and the number of firms impacted by a detonation in a particular site. It was not surprising that as the number of firms increased, the cost associated with the attack increased. In our case, 860 firms were affected directly, indirectly, and inductively by an attack on the central business district. The total cost of such an attack was estimated at $1.4 billion. In contrast, an attack on this city's industrial center was estimated to be $1.1 billion while affecting 580 firms. Although we do not suggest that this relationship could be used in lieu of an application of our entire method, it can be used in the early planning stages to facilitate early decision making in response to the threat. For researchers, this relationship between the number of firms within an area and the total effects in a particular detonation site can be used to validate the estimates generated from the method presented.

Despite all of the advantages, our method is not without limitations. The 1-mile radius for evacuation and the associated costs may be conservative as this radius does not reflect the plume of radioactive material (which shifts with the winds). Still, the economic disruption occurs with evacuations that are not typically driven by the predicted plume and instead based on a 360(potential hazard zone, effectively eliminating the wind direction considerations. Musolino and Harper,[38] in fact, discouraged the consideration of wind direction "especially in an urban setting where the wind field can be very complex." Although Musolino and Harper[38] suggested an initial 500-m radius, the 1-mile diameter still appears plausible as the psychological reactions to radioactivity are considered and these are coupled with the conservative nature of policy makers. Zeigler and Johnson[39] examined evacuation behavior in response to the TMI nuclear generating station. During non-nuclear emergencies, they concluded that individuals and families seem to evacuate based on direct sensory evidence of danger or explicit, convincing messages of impending danger. In contrast, individuals respond quite differently to nuclear accidents. Given that pregnant women and children aged below 5 years within 5 miles of TMI were encouraged to evacuate, approximately 500 pregnant women and 3,000 preschool children were expected to have left. In actuality, approximately 144,000 people within a 15-mile radius evacuated. This has also been substantiated in smaller, less potentially devastating incidents. As noted, 135,000 people in Brazil requested screening for exposure when only 249 people were actually exposed to radiation and 5,000 people who were never exposed to the materials showed psychosomatic symptoms of nausea that mimicked symptoms of actual exposure.[11] In summary, significant economic disruptions would likely occur and more nuanced models could be tested with subsequent research.

Moreover, this input-output modeling is unable to account for costs resulting from recovery, cleanup, or remediation efforts, instead focusing on the private sector losses in revenues and employment. Thus, planners should incorporate the costs that may be incurred through the recovery process that include police and fire department overtime, equipment that was damaged or expended in the response, and repair (or replacement) of government facilities (all of which may qualify for federal aid under the Stafford Act). Remediation costs associated with an RDD would likely include (a) the treatment and decontamination of victims, (b) evacuation and relocation of people from the affected area, (c) decontamination of the interior and exterior (or demolition) of affected buildings, (d) and safe discard of the radioactive debris. The costs of reconstruction and clean up after the September 11, 2001, World Trade Center attack might be at one end of the cost continuum. According to the Executive Director of the Port Authority of New York and New Jersey, these costs were approximately $16 billion with 1.5 million tons of debris removed.[16] Of course, this estimate would vary widely based on geographic region, but will be another cost in addition to the loss of employment and revenues explicated by our method.

Still, these recovery and remediation costs can be considered as a desired end state discussed among planners—a key part of Smith et al.'s[7] level of impact planning process. Unfortunately, no nationally, or internationally, acceptable levels of residual contamination[40,41] have been established. Generally, however, US Federal Guidelines, issued by the Environmental Protection Agency in 2009, have recommended reducing the cancer risk from remaining radiation to extremely low levels. Although abandonment or demolition might be an option, this may not be feasible in an urban area where thousands could lose their homes, jobs, and schools. Accordingly, these additional costs would be expected to be substantially valued at "hundreds of millions of dollars per site."[2]

Another shortcoming was our linear representation of economies of scale. We recognized that actual economies of scale are generally not linear; rather, they tend to follow a geometric or exponential growth curve. A linear approximation, however, is sufficient in that it better reflects the revenue distribution between small firms and large firms proportionally within an economy and is an improvement over estimates that hold economies of scale constant. In fact, this approximation confirmed differences between a method that accounted for economies of scale and one that did not. In addition, we found that the accuracy lost by applying a linear function to the economies of scale did not appear substantial enough to warrant the more complex modeling that would be required for this method to be practical. Still, we recommend future research to be done to explore differing models for economies of scale.

Along with the limitations presenting opportunities for researchers, we would recommend several other research avenues as well. First, we recommend repeated iterations using our method in various metropolitan areas to further validate our work and, more importantly perhaps, to provide new insights into the effects and interactions between distinct intracity regions. Clearly, different sites of similar type would have varying revenues and factors associated with that particular location. Yet, there may be similarities that can help the planning process across regions. Although we focused on the commercial economic impacts, we would also recommend future researchers to quantify other impacts. Residential considerations are particularly interesting because residential areas do present an attractive target to terrorists given their fear-striking motive. An attack in a residential area would not only a direct effect on residential property values but also have significant indirect and induced costs triggered by the exodus of people from the impacted area. Moreover, costs would also be linked to other psychological factors that arise with RDDs. We also did not examine the costs associated with disruptions in traffic flows; these costs when considered would undoubtedly increase the indirect and induced costs associated with an RDD.

Even with these limitations, we have illustrated that the economic fallout resulting from an RDD has the potential to be quite devastating. If recovery and resiliency to an RDD are to be maximized, effective and efficient planning is critical. Accordingly, we recommend that officials and planners at all levels of government to assume a proactive posture as this threat is considered. By conducting an economic impact analysis, key stakeholders can attain a better understanding of the possible magnitudes and ranges of possible economic impacts resulting from an RDD. From these results, they can better determine where to allocate limited resources to prevent or even deter an RDD attack. The method we outline serves as a tool that can guide officials in any location to facilitate their planning and decision making. We applied the method to three distinct regions of a mid-sized urban economy but it can be used by any city throughout the United States to determine the effects (direct, indirect, and induced) that an RDE would have on the economy. As an initial estimate, we recommend leaders to compute the economic impacts based on the relationship between the effect of the impact and the density of firms surrounding the RDD site, a relationship discovered as part of our analysis. From all of this, preventive measures can be in place, resources can be efficiently allocated, and recovery and resiliency can be maximized before the RDD occurs.

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