# Integrated GIS-based Optimization of Municipal Infrastructure Maintenance Planning

**Altayeb Qasem[1] & Dr. Amin Hammad[2]**

[1] Department of Building, Civil& Environmental Engineering

[2] Concordia Institute for Information Systems Engineering (CIISE)

# Agenda

- Research motivations
- Objectives
- Infrastructure deterioration
- Integrated infrastructure management
- Proposed approach
- Case study
- Summary and future work

# Infrastructures Conditions In Canada

- Most Canadian cities emphasis has been placed on new construction for the past three decades which caused major deterioration to old facilities. (Vanier and Danylo, 1998)

- There is currently maintenance accumulated shortfall estimated at $44 billion to return these assets to an acceptable condition. (FCM, 1996).

- Canadian municipalities spend about CAD $15 billion per year on infrastructure of which 80% is spent over repair and renewal operations of the old existing infrastructures. (CWWA 1997

# Infrastructures Conditions in The U.S.A.

- The American infrastructure facilities have the following rating:

| | |
|---|---|
| Bridges | C |
| Transit | D+ |
| Drinking Water | D- |
| Wastewater | D- |
| Roads | D |
| Dams | D |

(ASCE 2005)

# Municipalities Current Challenges

- Knowing the Infrastructure facilities conditions.
- The absence of standard infrastructure rating system.
- The absence of clear standard MR&R prioritization system.
- Growing municipal budget deficit.
- Lack of standard prioritization procedure.
- Lack of collaboration among different municipalities to manage their shared infrastructure facilities.

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# Objectives

- To investigate different deterioration rating techniques for different infrastructure facilities.
- To investigate the suitability of different infrastructure rehabilitation techniques based on spatio-temporal analysis.
- To use a GIS as an integration platform to visualize the prioritized rated facilities.
- To investigate the applicability of genetic algorithms for optimizing the integrated plans.

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# Factors Affecting Infrastructure Facilities Deterioration

- Infrastructure facilities deterioration is a function based on many parameters that can be classified into the following categories:
  - Physical parameters (material used, construction method, etc.)
  - Operational parameters (traffic volume, speed, vehicle loads, etc.)
  - Environmental parameters (soil corrosively, soil texture, etc.)

# Infrastructure Deterioration Models

- Deterioration models are used to:
  - Evaluate current asset conditions.
  - Predict best rehabilitation procedure & timing.
  - Predict the future conditions of infrastructure facilities.
  - Quantify the deterioration in different facilities based on stochastic or deterministic analysis.

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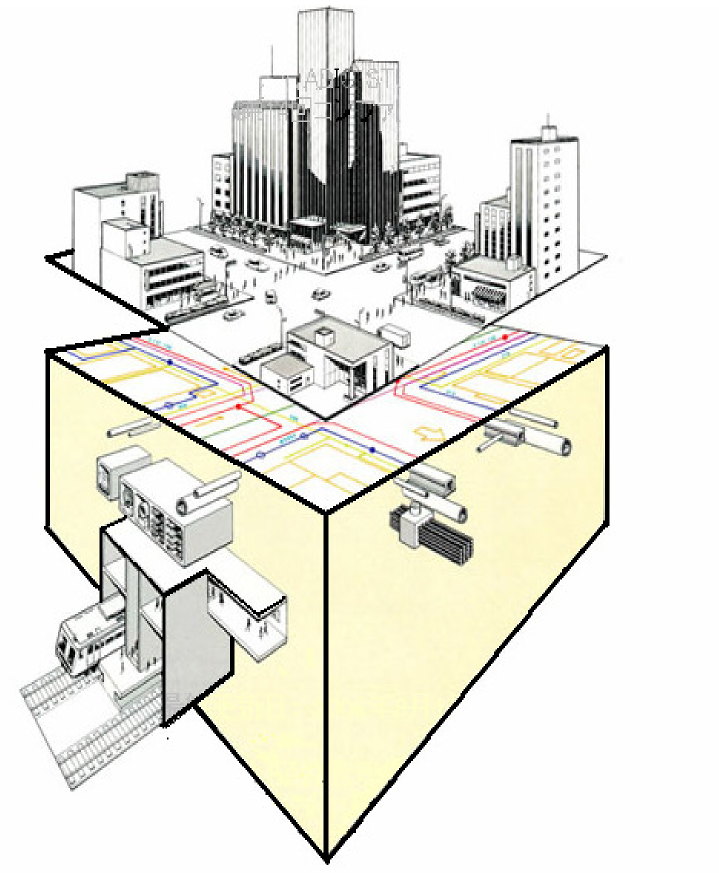
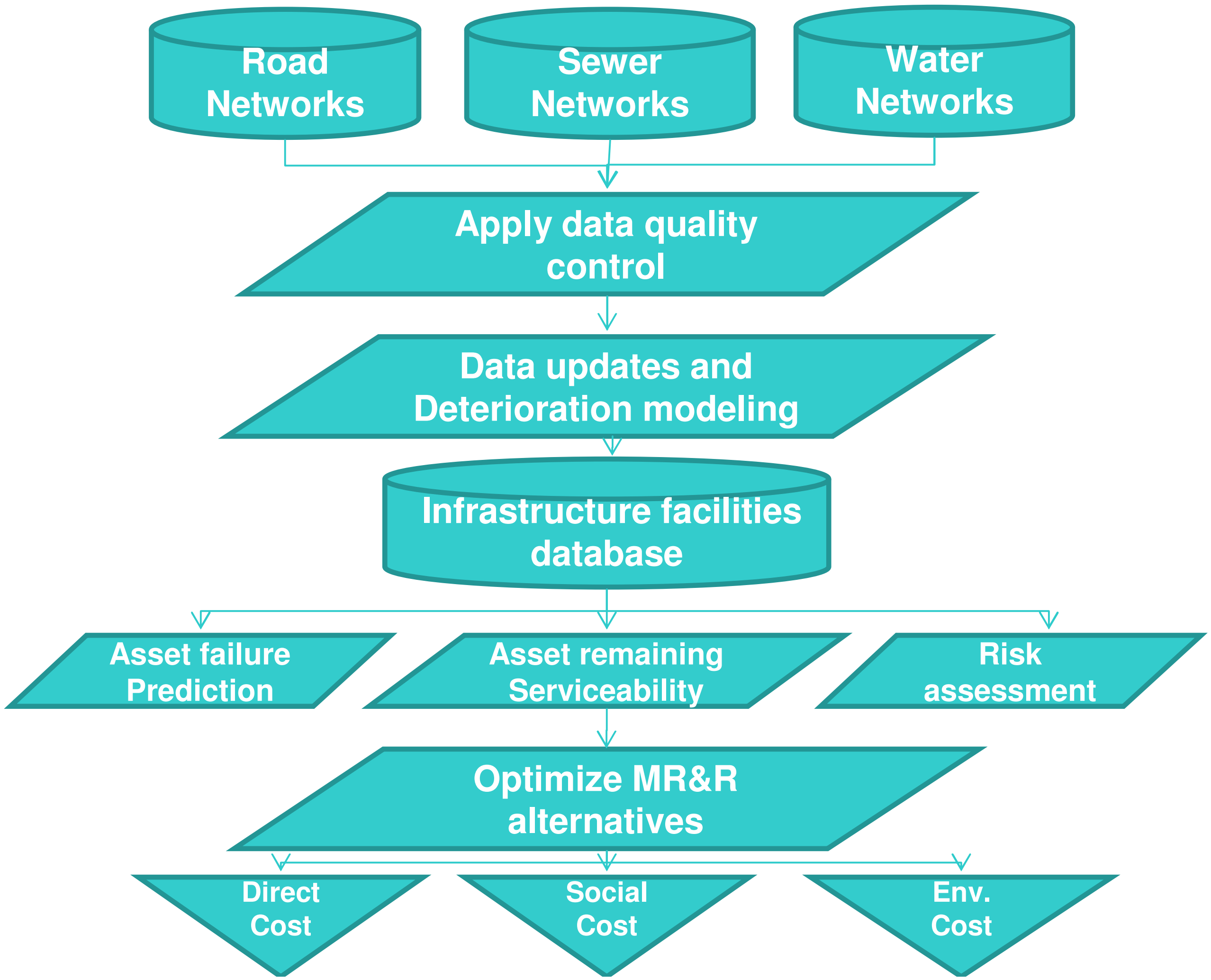
# Integrated Infrastructure Management Approach (IIMA)

- Several infrastructure facilities usually are buried within certain proximity under roads.
- Sharing the same space dictates the importance of applying integrated MR&R interventions.
- This MR&R integration dictates spatial integration factors that need to be carefully analyzed.
- This integration is expected to reduce the lifecycle costs and the social and environmental impacts.



Source: http://www.roadic.or.jp

# Required Data for MR&R Optimization (Proposed)



# Spatio-Temporal Analysis

- Spatio-temporal analysis refers to the relationship integrating time and space as the primary dimensions of data for spatio-temporal processes.

(Xiaobai 2003)

- Spatio-temporal relationship depends on information technologies to visualize space, time and their analysis.

# Dynamic Segmentation

- Dynamic segmentation is a process of transforming linearly referenced data (commonly called events) stored in a table into a feature that can be displayed on a map.

(ESRI 2007)

# Dynamic Segmentation Requirements

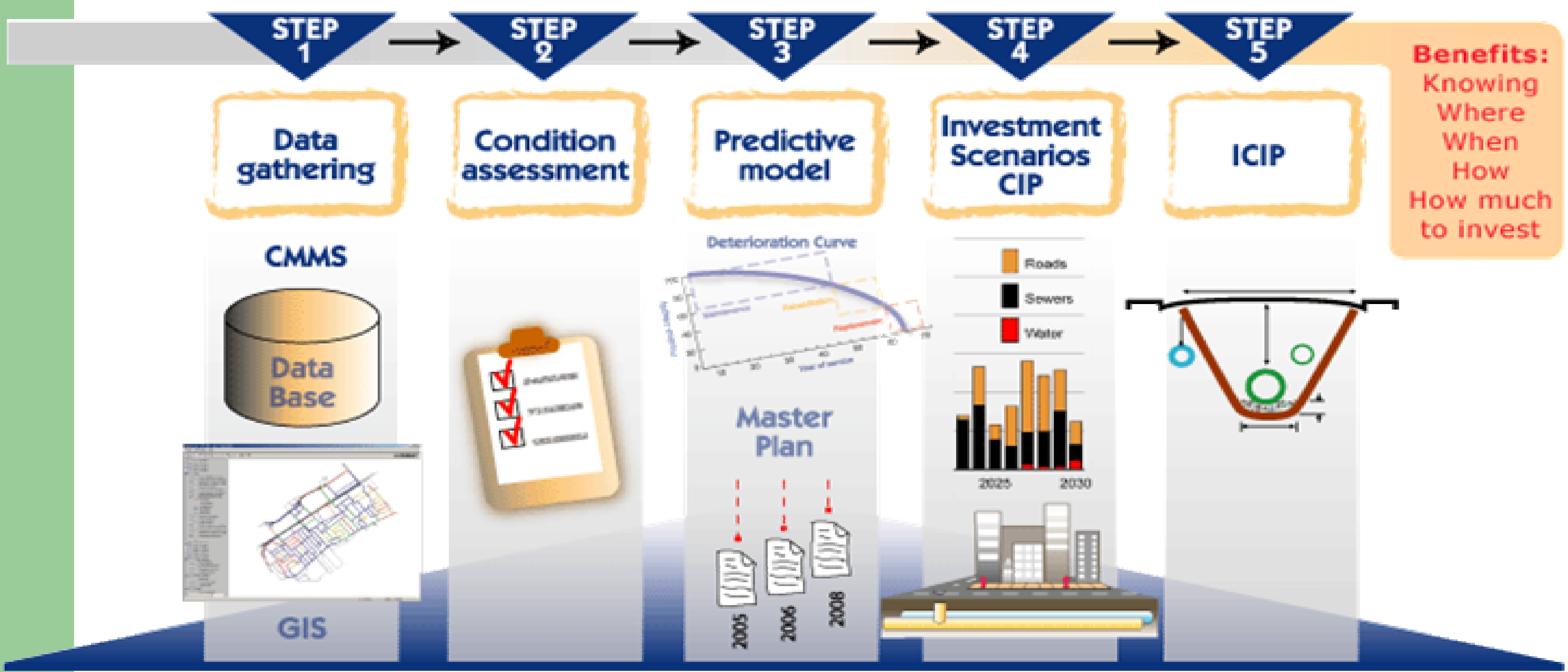
- To perform dynamic segmentation, the data must satisfy the following two requirements:
  - First, each event in an event table must include a unique identifier and its measurement along a linear feature.
  - Second, each linear feature (commonly called a route) must have a unique identifier and a measurement system stored with it.

(Cadkin & Brennan, 2002)

# GISs Role in the Integration Process

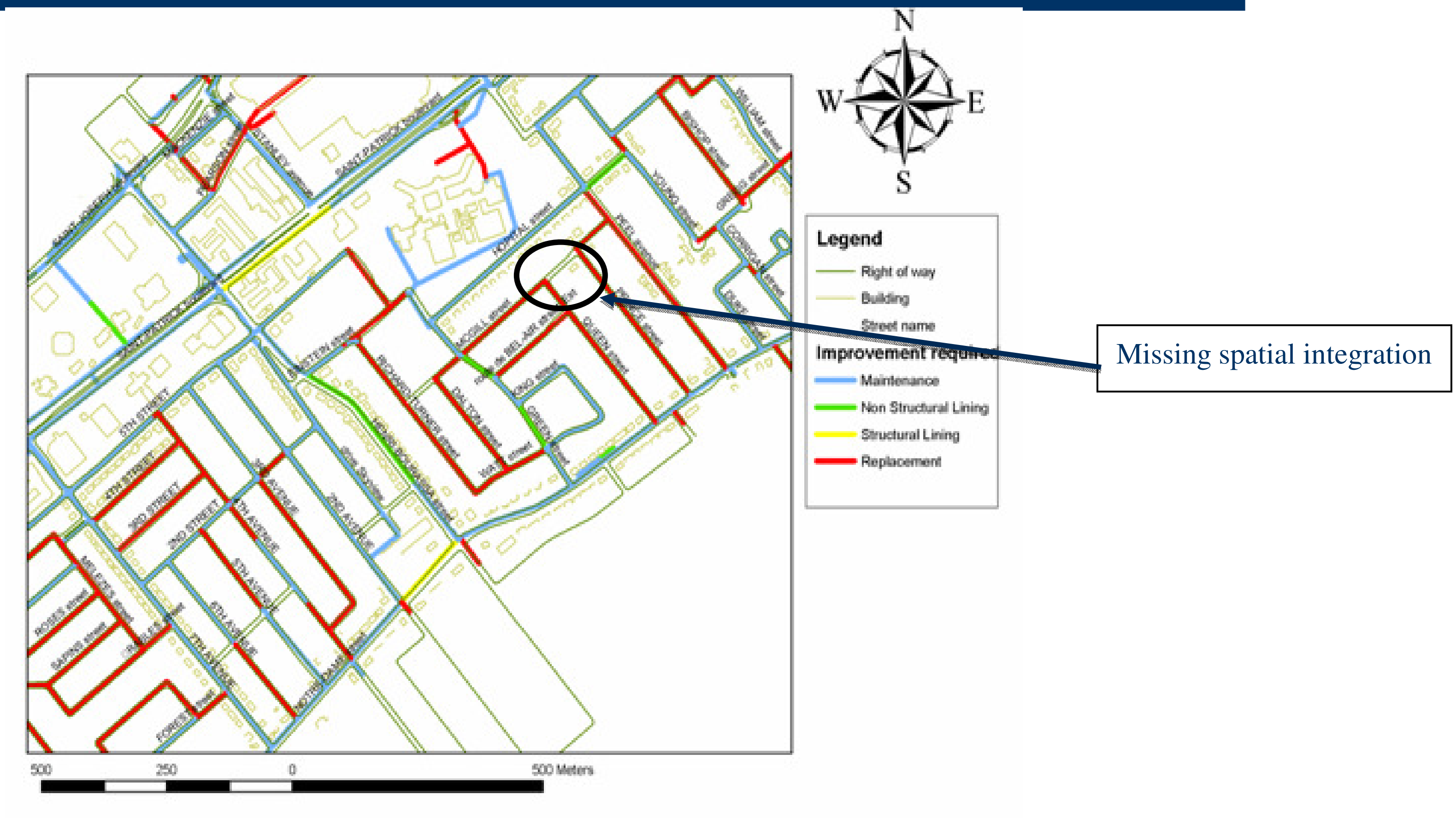
- GISs can be used as the integration platform for IIMS, which is designed to manage the needs of different infrastructure components.
- GISs can show the proximity of different facilities which will make it possible to visualize their interrelationships.
- GISs help in realizing the needs and impacts of different MR&R methods over different facilities.
- GISs well defined attributes are an important tool to characterize different infrastructure facilities.
- GIS tools, such as segmentations tools, are required to do the integrated analysis.

# Harfan Integrated Management Approach




(Harfan 2006)

# Project Level Optimization




Harfan's IDSS



Lalonde É 2002

# SAGE: Systeme d'aide a la gestion et a l'entretien

- SAGE establishes a framework of an information system that integrates the maintenance activities of civil municipal infrastructure (road, sewer, and water networks).
- SAGE justifies the feasibility of integrating various infrastructure components in the same decision system, and quantifies the value of this integration.
- SAGE was programmed using visual basic, and obtains various infrastructure data from a Microsoft Access data base.

(Bruxelle 2005)

# SAGE Optimization Approach

(Bruxelle 2005)

Minimize $$\sum_{u=1}^{o}\sum_{s=1}^{n}\sum_{t=1}^{m}\sum_{a=1}^{k} x_{sta}^{u} C_{sta}^{u}$$

Subject to $$\sum_{a=1}^{k} x_{sta}^{u} = 1 \forall t, s, u \qquad x_{sta}^{u} = \begin{cases} 0 \\ 1 \end{cases}$$

$$Q_{t+1}^{u} = Q_{t}^{u} + x_{sta}^{u} \Delta Q_{a}^{u} \geq Q_{\min}^{u}$$

•Simplex method was applied to optimize the objective function.

•The minimum acceptable quality for each facility is the constraint of this optimization.

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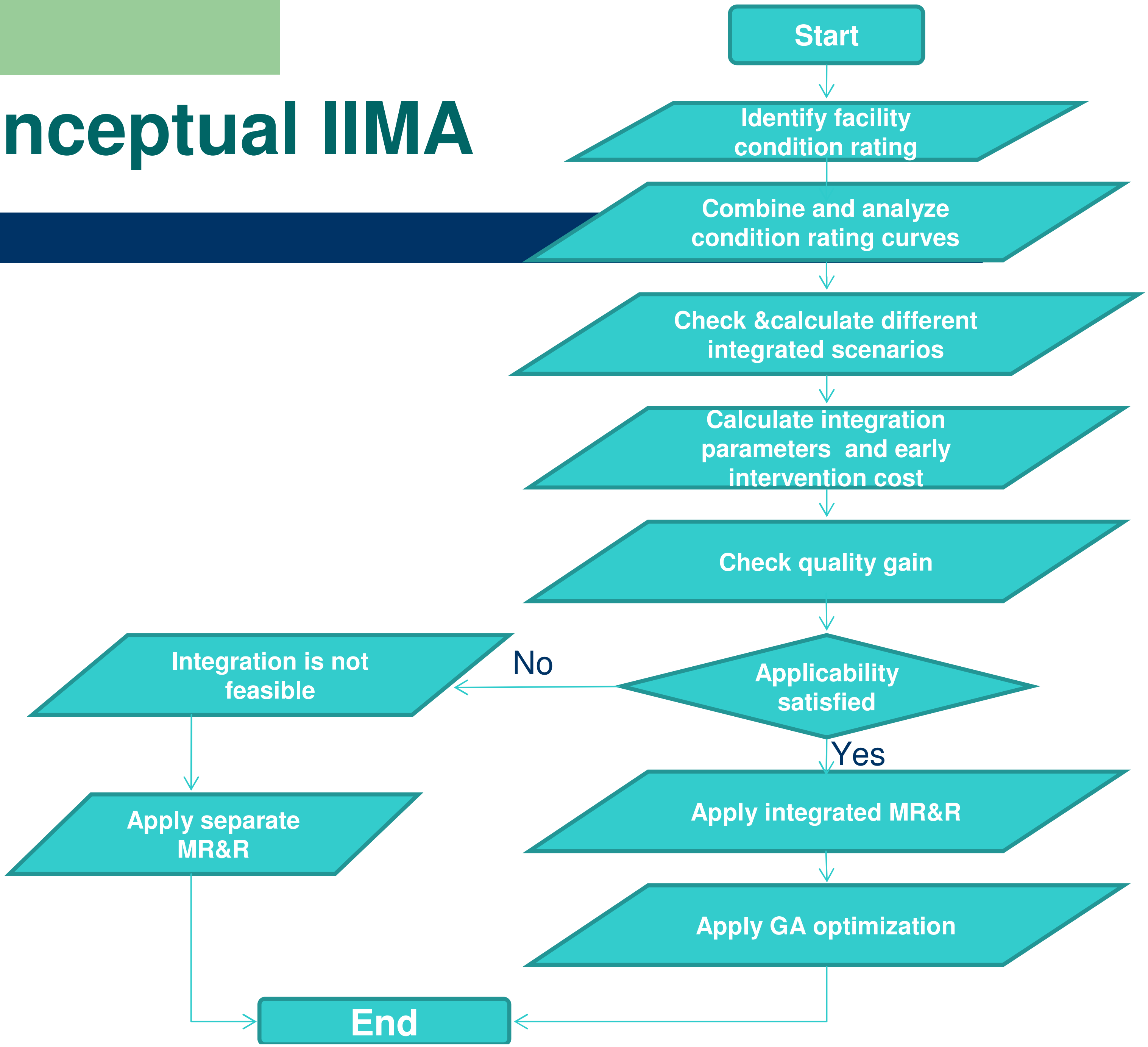
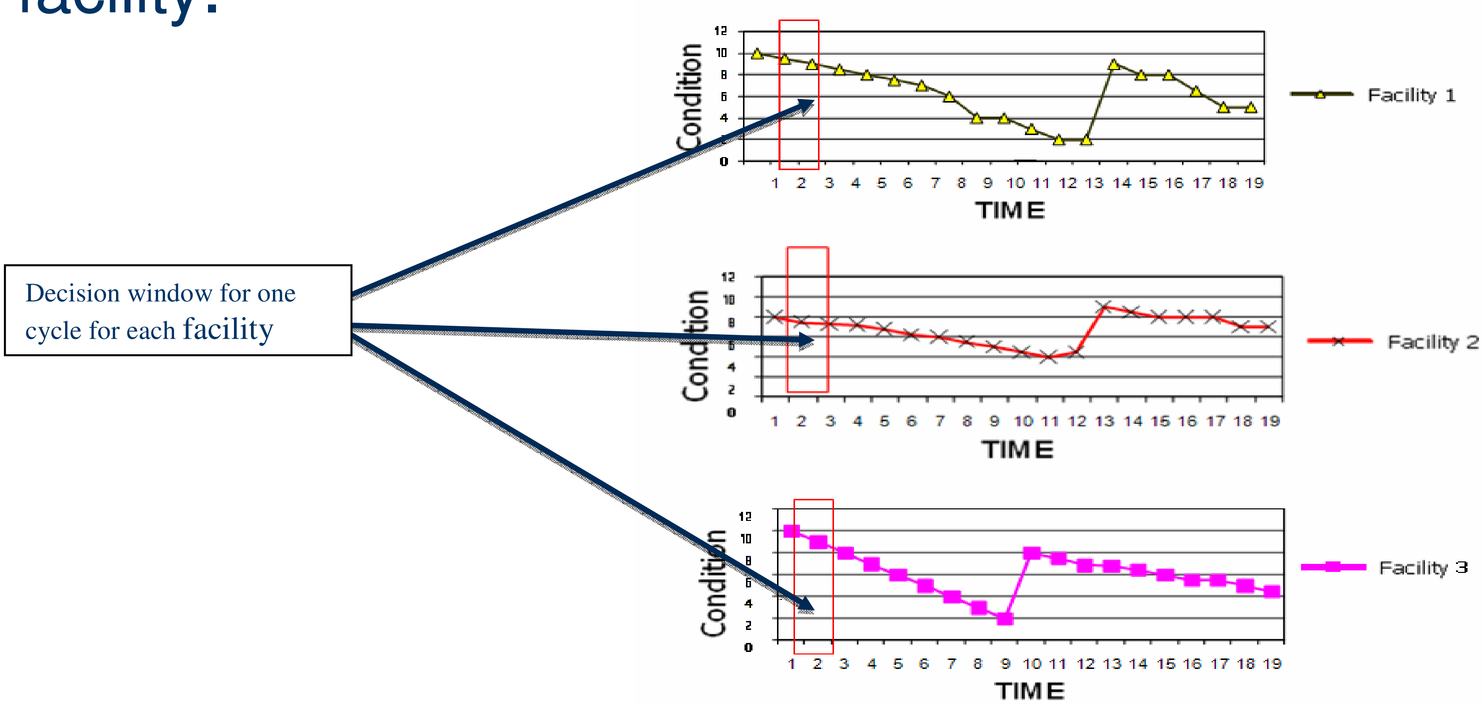
# Conceptual IIMA



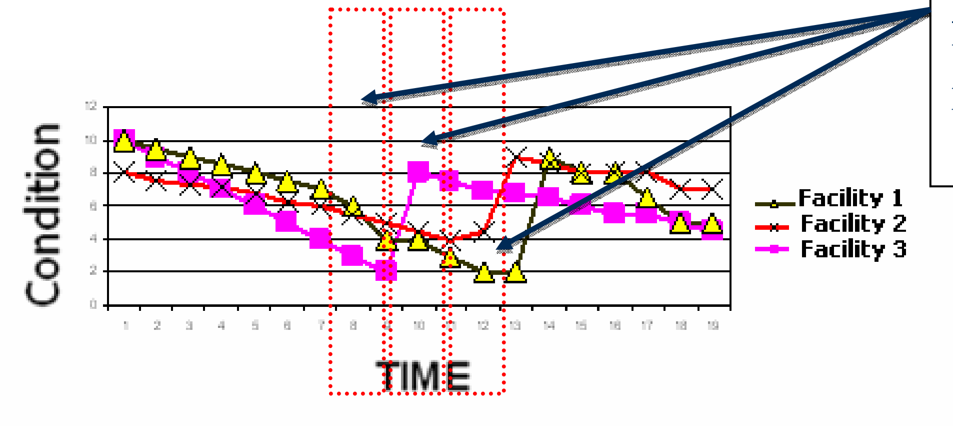
# The Proposed IIMA

- Each facility deteriorates based on its own physical operating and environmental conditions curve.
- These deterioration curves must be identified for each facility.



# The IIMA Proposed Approach (Cont.)

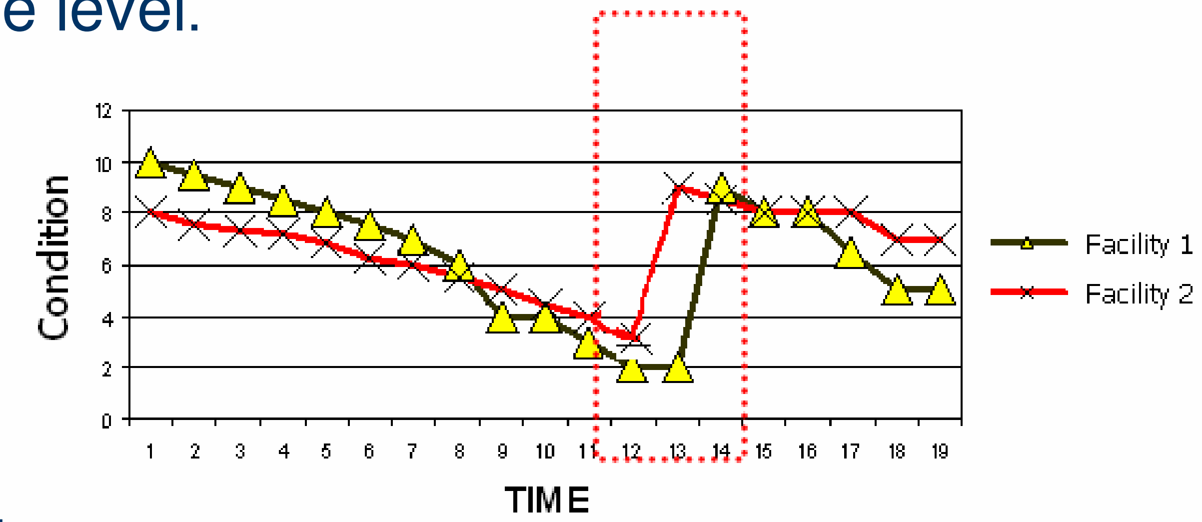
- Deterioration curves of different municipal facilities are combined in a single graph to show the extent of each facility's deterioration.




Optimizing the best timing for rehabilitation that integrates all facilities

# Integration Scenarios

– The first scenario: Apply MR&R integration when the deterioration level of more than one facility reaches the unacceptable level.



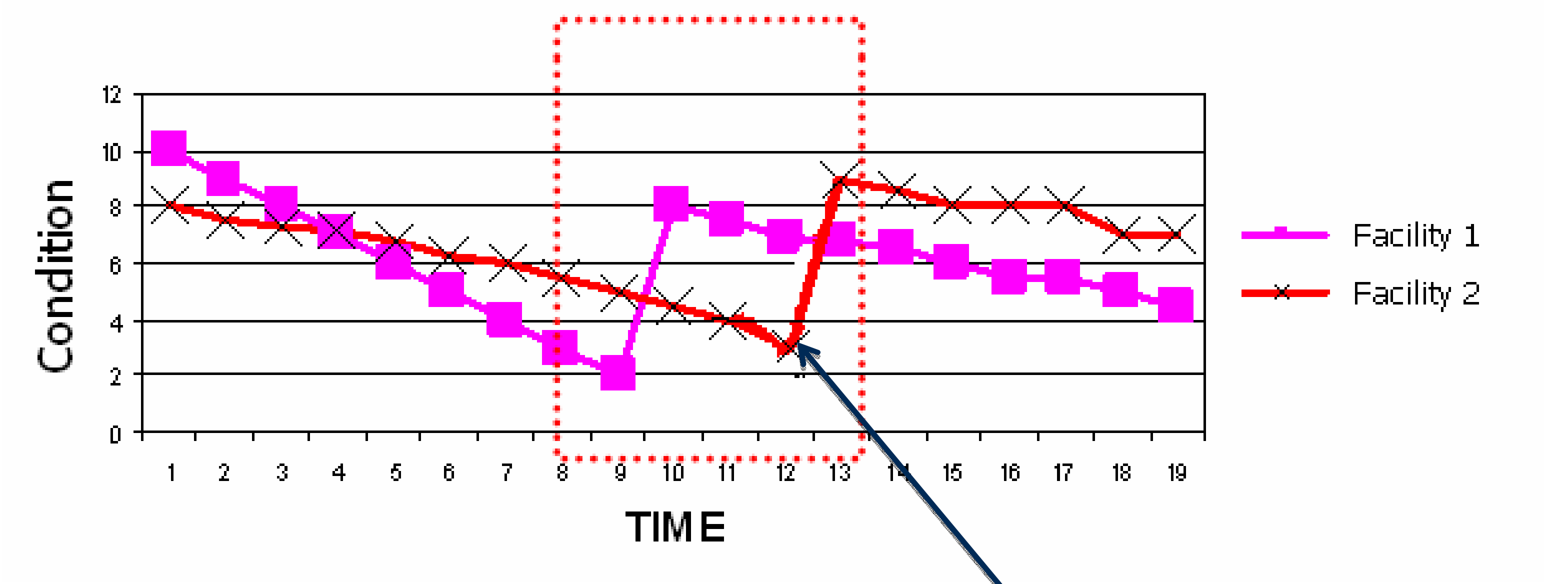

$$C = (C_1 + C_2)\beta\gamma$$

where:

| | |
|---|---|
| $C$ | integrated cost. |
| $C_1, C_2$ | the cost of applying MR&R intervention to facility 1 and facility 2, respectively. |
| $\beta$ | reduction factor of direct costs. |
| $\gamma$ | reduction factor of social and environmental costs. |

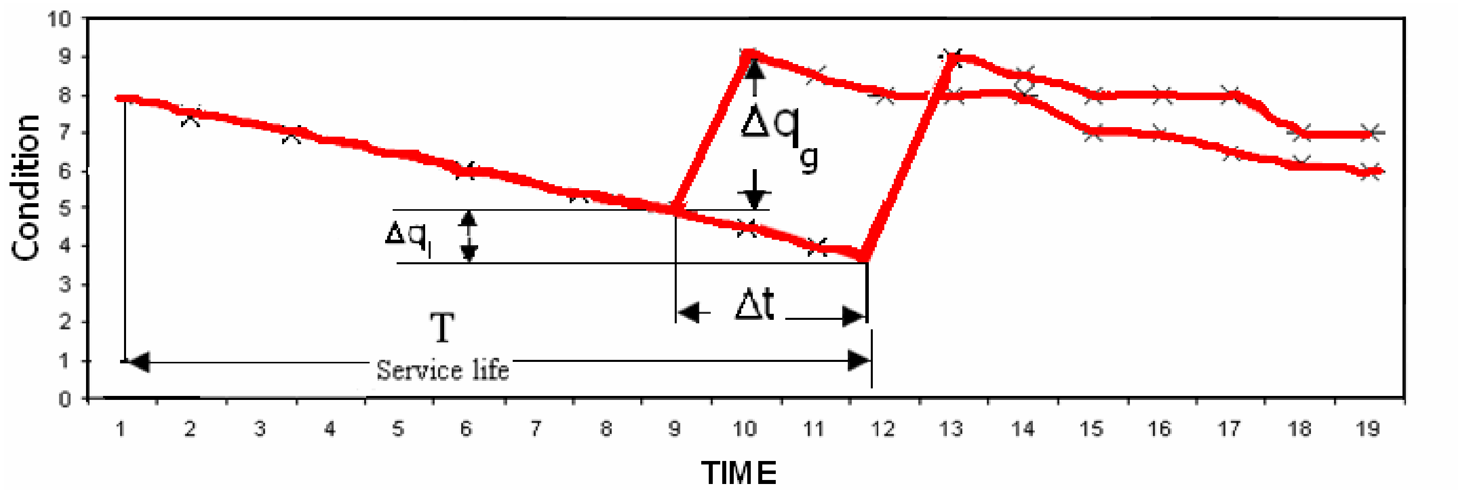
# Integration Scenarios (Cont.)

– The second scenario: Apply MR&R integration when a certain facility's deterioration reaches the unacceptable level and the other facilities are still in the acceptable level.




Early intervention will scarifies the remaining service life

# Remaining Life Scarifies




$\alpha = 1 + \Delta t \ / T$

$A = \Delta q_g / \Delta q_l > 1$

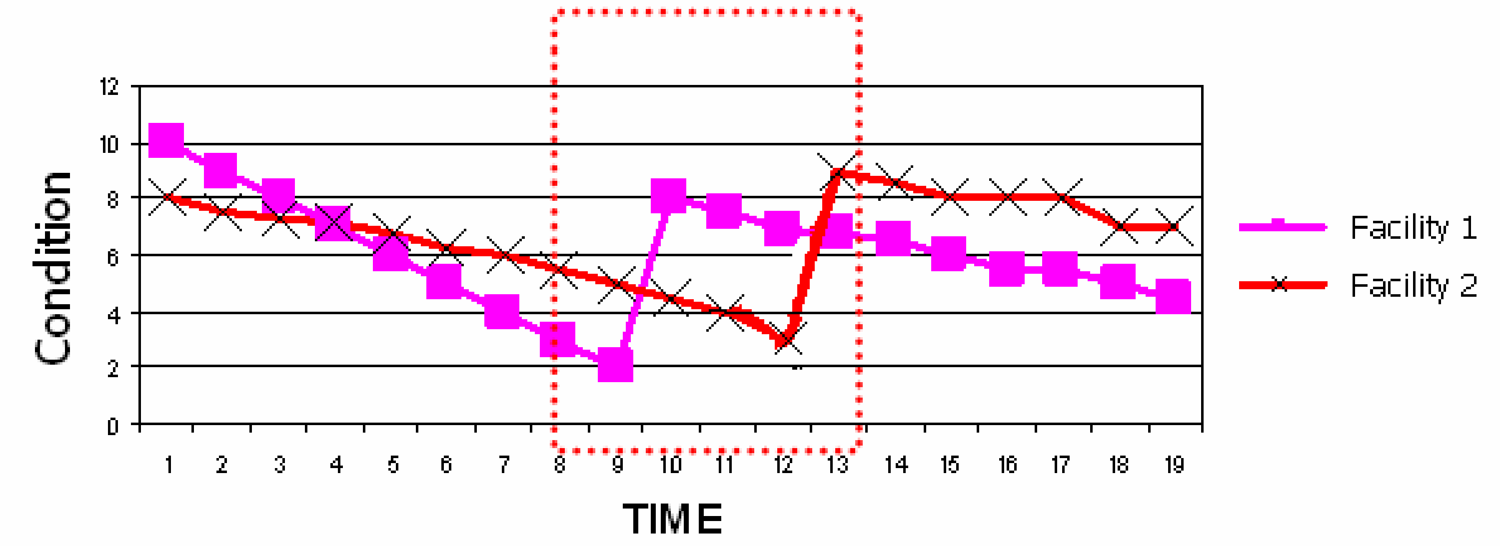
where:

| | |
|---|---|
| $\alpha$ | early intervention factor |
| $\Delta t$ | scarified remaining life. |
| T | facility service life |

| | |
|---|---|
| $A$ | MR&R integration applicability factor |
| $\Delta q_l$ | is the quality loss due to early intervention |
| $\Delta q_g$ | is the quality gain due to the selected MR&R method |

# Optimization

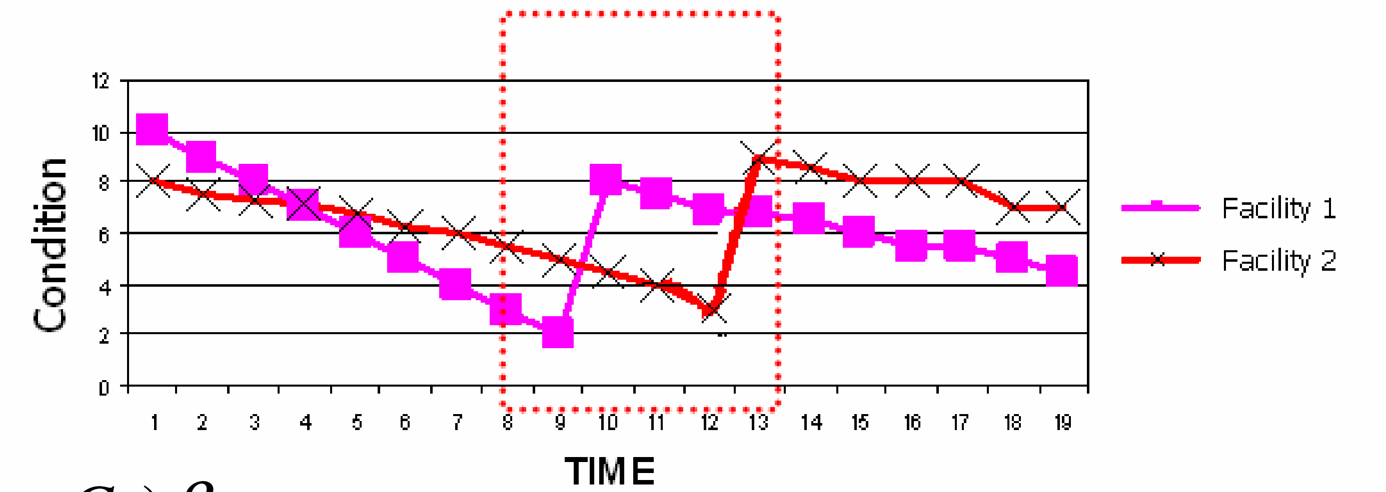
– The integration cost for the second scenario




integrated $C = (C_1 + \alpha C_2)\beta\ \gamma$

# Numerical Example

(based on the second scenario)

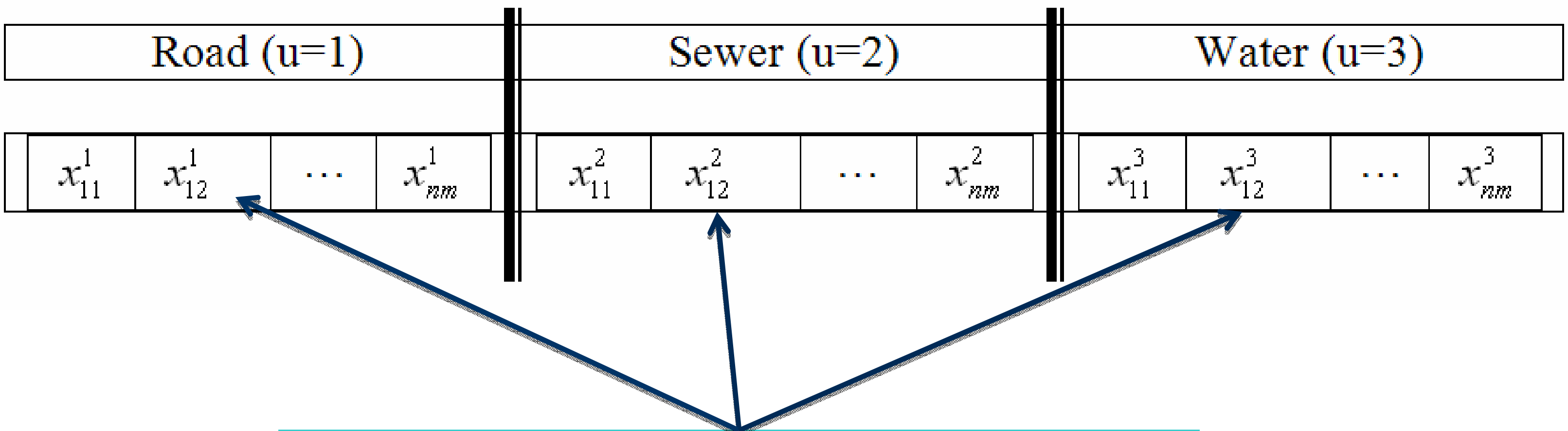



$$C' = (C_1 + \alpha C_2)\beta\,\gamma$$

| Utility | MR&R decision | $C_i$ | $\alpha$ | $\beta$ | $\gamma$ | $C'$ | $\Delta C$ |
|---|---|---|---|---|---|---|---|
| Water section | Replacement | $12,000 | 1 | 0.75 | 0.95 | $8,550 | $3,450 |
| Sewer section | Replacement | $9,000 | 1.1 | 0.75 | 0.95 | $7,053 | $1,947 |
| Total cost | | $21,000 | | | | $15,603 | $5,397 |

# Genetic Algorithm (GA)

Proposed GA gene design




The value of a cell represents the action for *a* specific section at time *t*.

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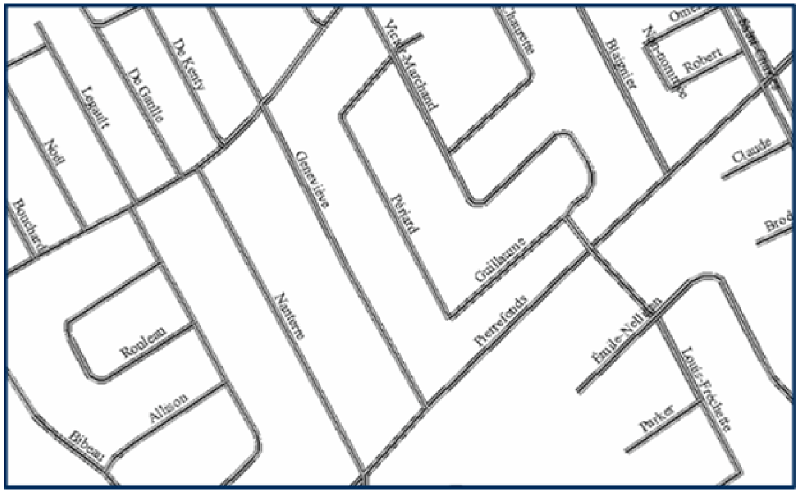
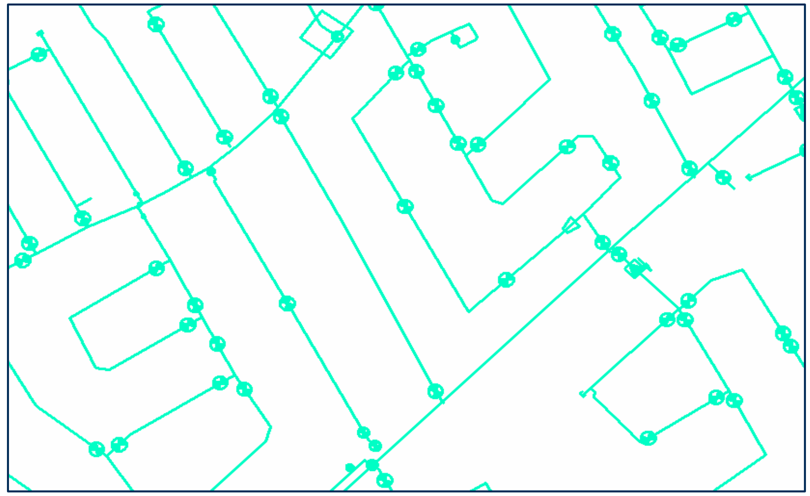
# On Going Case Study

- Part of Pierrefonds municipal facilities.



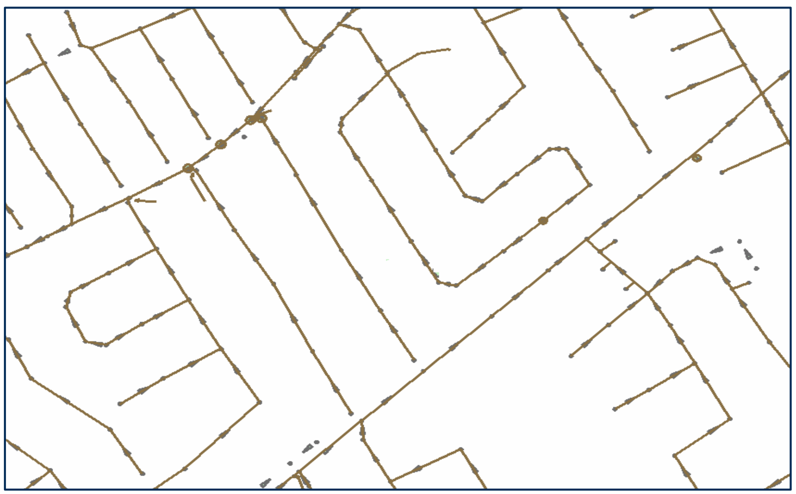

Roads network



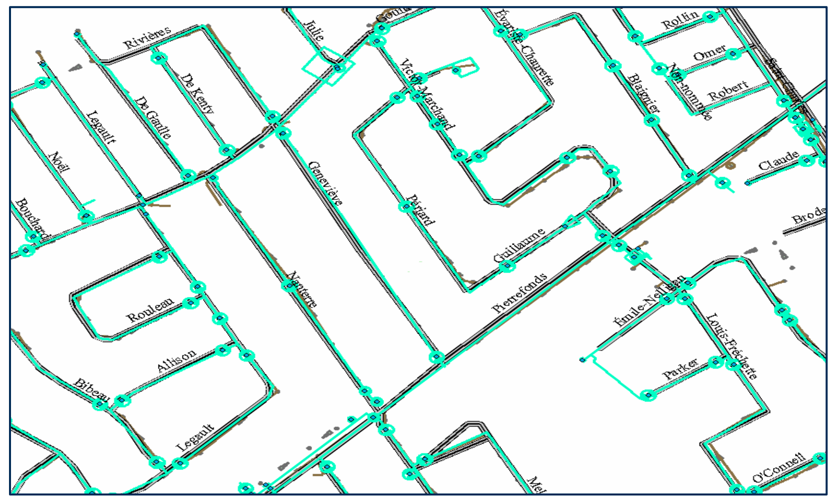
Water network

# On Going Case Study (Cont.)

- Part of Pierrefonds municipal facilities.

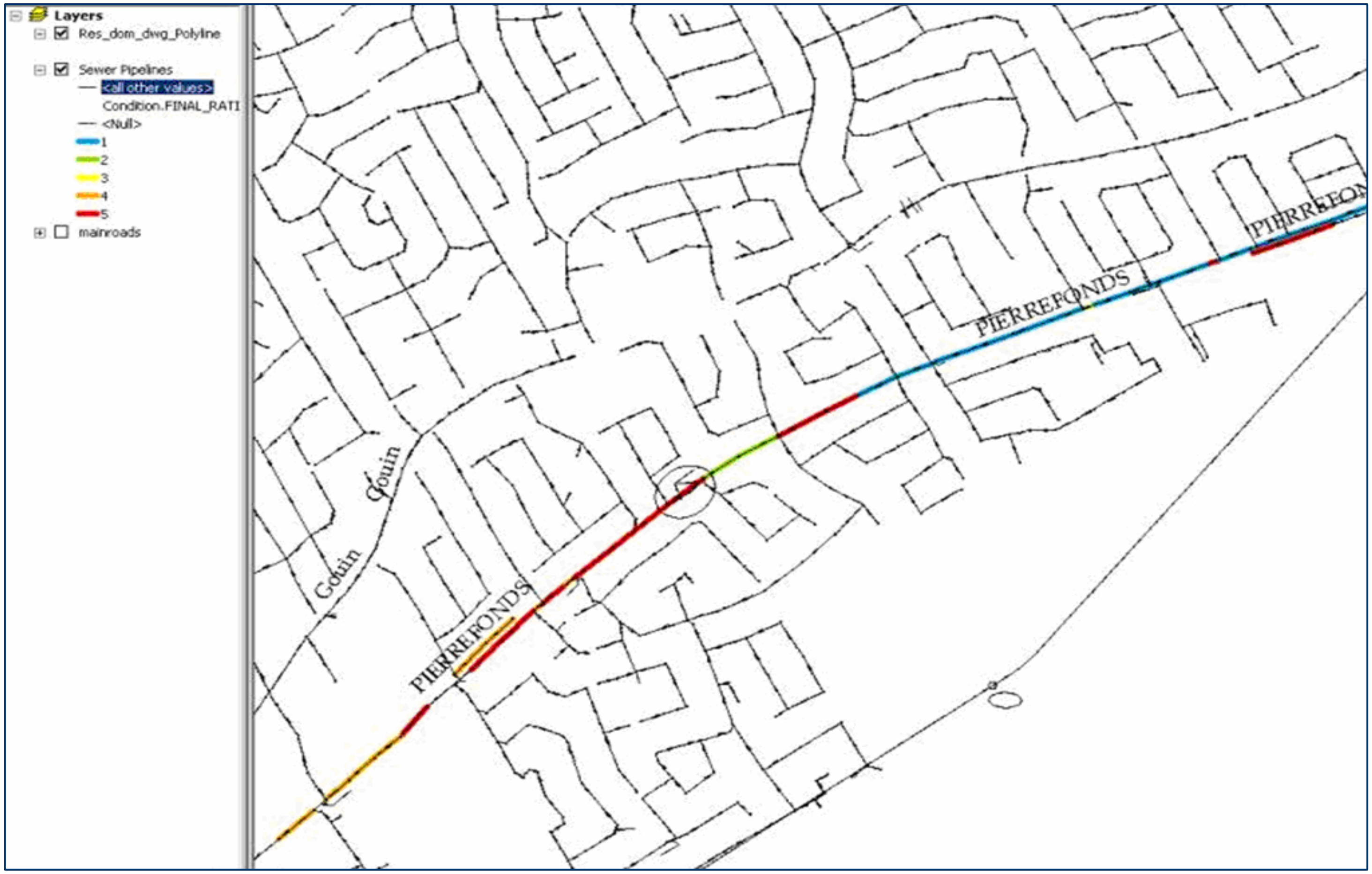


Sewer network




Municipal facilities overlapped networks

# Pierrefonds Rated Sewer Sections



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# Summary And Future Work

- Municipalities are required to identify their infrastructure facilities based on their condition rating.
- Typically condition rating is done by direct inspection which is economically not feasible, this study shows that this problem can be solved by adopting different condition rating models.
- Knowing the condition rating of different facilities is the key factor in applying the IIMA.
- IIMA is expected to reduce the long term infrastructure management costs.
- The main contributions of this paper are:
  - Discussing the IIMA different scenarios.
  - Defining the cost of the remaining service life loss.
  - Introducing the spatio-temporal project level optimization.

# Summary And Future Work (Cont.)

- The future work related to this study is as follows:
  - Defining specific MR&R actions for different infrastructure facilities and their integration parameters ($\alpha, \beta, \gamma$, and $A$).
  - Identifying the quality gain of each MR&R action and for different facilities.
  - Preparing GA optimization requirements (gene design, crossover, and mutation processes).
  - Applying dynamic segmentation to Pierrefonds data and using it in the GIS.

Thank you