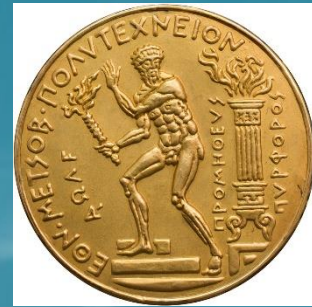




NATIONAL TECHNICAL UNIVERSITY OF ATHENS  
SCHOOL OF CIVIL ENGINEERING  
VELTION GROUP



**ImSafer**

information modelling for safer structures



**H.F.R.I.**  
Hellenic Foundation for  
Research & Innovation

Hellenic Foundation for Research and Innovation

**Project Fiche**



Proposal ID: **00356**

Acronym: **IMSAFER**

# Fire-Safety Upgrading of Historic Structures

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5<sup>th</sup> International Winter School in Structural Morphology  
Structural Morphologies for Archaeological and Historical Sites



**Cultural Heritage**

**Fire Protection  
Design**

**Performance-  
Based Design**

**Optimization**

**Optimized  
Performance-Based  
Fire Protection  
Design/Upgrading of  
Cultural Heritage**





## Buildings of Cultural Heritage and Fire Risk



Chiado (centre of Lisbon), Portugal, 1988



## Buildings of Cultural Heritage and Fire Risk



Parliament of Brittany,  
Rennes, France, 1994



Theatre Fenice,  
Venezia, Italy, 1996

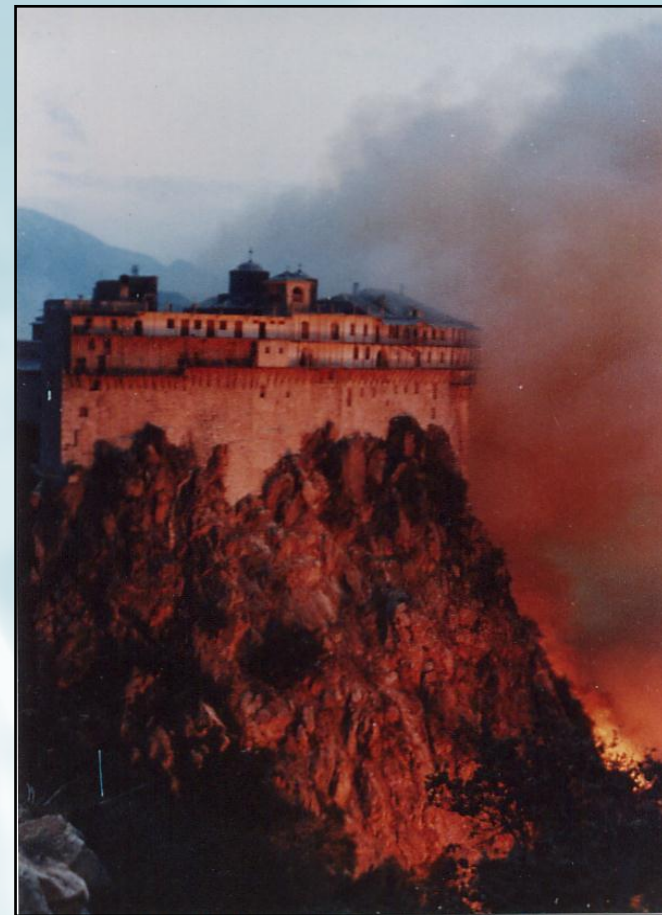


Windsor Castle,  
England, 1992





## Buildings of Cultural Heritage and Fire Risk



Monastery of Simonos Petra, Mount Athos, Greece, 1990



## Buildings of Cultural Heritage and Fire Risk



Thessaloniki, Greece, 2005





## Buildings of Cultural Heritage and Fire Risk



Historic centre of Lefkas Island, Greece, 2016



## Buildings of Cultural Heritage – Fire Protection

When it comes to historic buildings, fire protection measures do not only aim at **protecting the human life** but should as well take care of both the **building itself** and in specific cases **its contents**

### Characteristics of historic buildings:

- Historic buildings are carriers of memory and culture.
- Historic buildings are existing buildings.
- Historic buildings are often very old.
- Historic buildings are often not used for the purposes that were designed for (i.e. houses that are currently used as offices, museums, galleries etc.).





# Buildings of Cultural Heritage – Fire Protection

## Fire protection measures

- M1 - compartmentation,**
- M2 - fire resistance of structural elements,**
- M3 - control of fire load,**
- M4 - materials (reaction to fire),**
- M5 - control of fire spread outside the building,**
- M6 - design of means of escape,**
- M7 - signs and safety lighting,**
- M8 - access of the fire brigade,**
- M9 - detection and alarm,**
- M10 - suppression and extinguishing,**
- M11 - smoke control systems,**
- M12 - training of the personnel,**
- M13 - fire drills and emergency planning,**
- M14 - management of fire safety,**
- M15 - maintenance of fire safety system,**
- M16 - salvage operation**



## Buildings of Cultural Heritage – Fire Protection

M1

M2

M3

M4

M5

M6

M7

M8

M9

M10

M11

M12

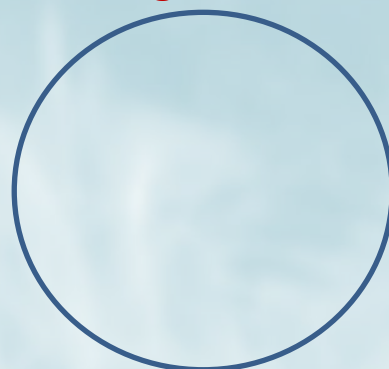
M13

M14

M15

M16

Measures of very  
high cost



Measures of  
high cost



Measures of  
low cost



Measures of very  
low cost







## Analytical Hierarchy Process – AHP

### Decision Making

- (i) **Problem analysis;** This step includes the decomposition of the problem and the identification of the primary objective or goal of the decision-making process. An uncaredful work analyzing the problem, failing to detect all its parameters and determine all the possible criteria of the deciders, could result to misleading solutions,
- (ii) **Selection of the alternative solutions;** It is important for the decider to have a decent number of alternatives to choose in order to increase the possibility to reach the optimized solution,
- (iii) **Evaluation of the alternative solutions and adoption of the optimum one;** This step includes se-lection of the weighting method to assess the importance of the criteria identified in previous steps,
- (iv) **Application and verification of the final decision;** Usually the final step includes the monitoring of the whole process and its success is closely related to the adequacy of it.



# Analytical Hierarchy Process – AHP

## Multiple Criteria Decision Making - MCDM

International Society on Multiple Criteria Decision Making

### Definition

*«MCDM can be defined as the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process».*





## Analytical Hierarchy Process – AHP

Thomas L. Saaty

- AHP is an extensively popular technique for addressing MCDM problems,
- providing a rational, structured and comprehensive framework which facilitates the efficient formulation of the decision problem,
- the representation and quantification of its elements, the correlation of those elements to the objectives and overall target or goal, and the evaluation of the alternative solutions that were reached through this process.



## Analytical Hierarchy Process – AHP

Generally speaking, the application of AHP is based on the four following steps:

**1<sup>st</sup> Step:** The first concern is to decompose the problem into its components, namely policy or main goal, objectives, strategies and measures.

**2<sup>nd</sup> Step:** The prioritization of the hierarchy elements of each level is the next step to determine the hierarchy interconnections.

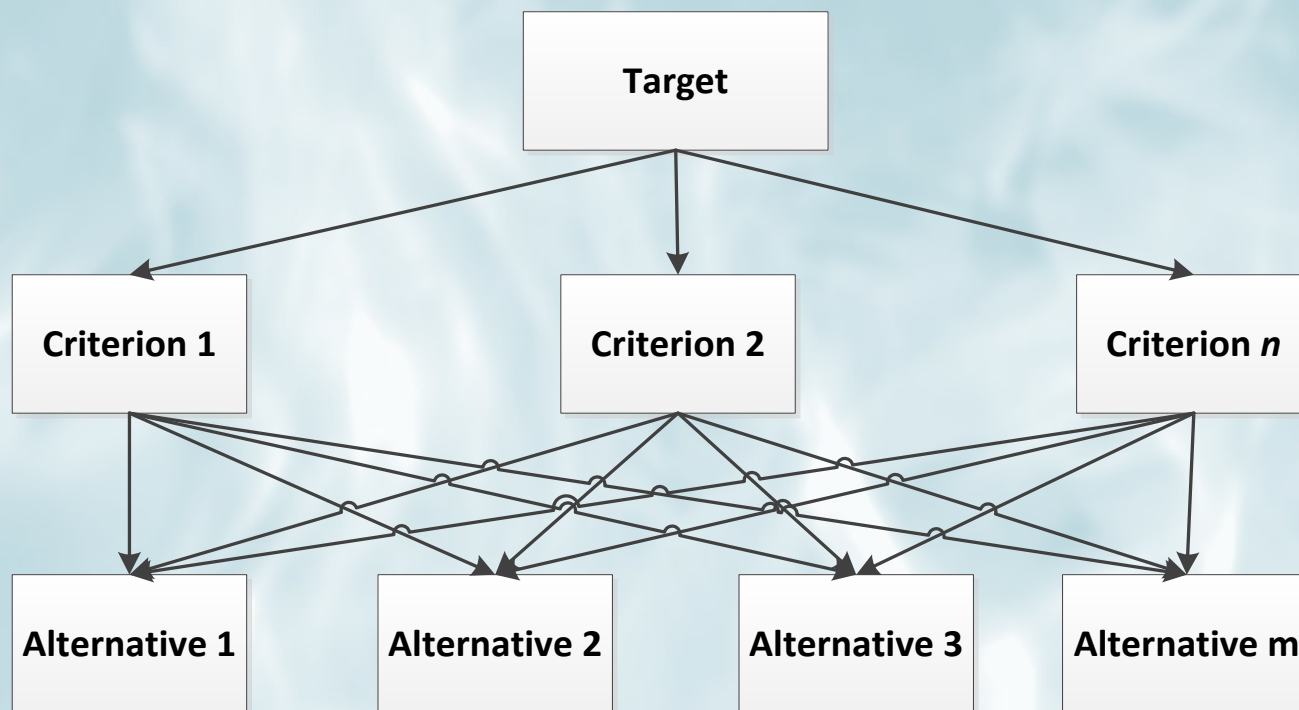
**3<sup>rd</sup> Step:** Having determine scaling, the normalization of weight coefficients of every element is calculated aiming to define the correlation of each element with the elements of the level above.

**4<sup>th</sup> Step:** The final step includes the synthesis or recomposing of the elements, based both on their normalized weight coefficients and the application grade of the fire protection measures, as will be detailed discussed in the following sections.





## Analytical Hierarchy Process – AHP



Typical form of AHP tree



## Fire Risk Management

Fire risk is defined according to the ISO/PDTS 16732 standard, as:

- When "risk of a potential event" defines the combination of the probabilities of that event and its consequences.
- When "risk of a study plan" defines the combination of the probabilities of all the events involved in the design of the study.

### Fire risk analysis:

1. Identification of possible causes (dangers) of fire
2. Quantification of the consequences and the probability of the risks
3. Identification of control (risk) options
4. Quantifying the impact of these options on security
5. Selection of appropriate protection measures.

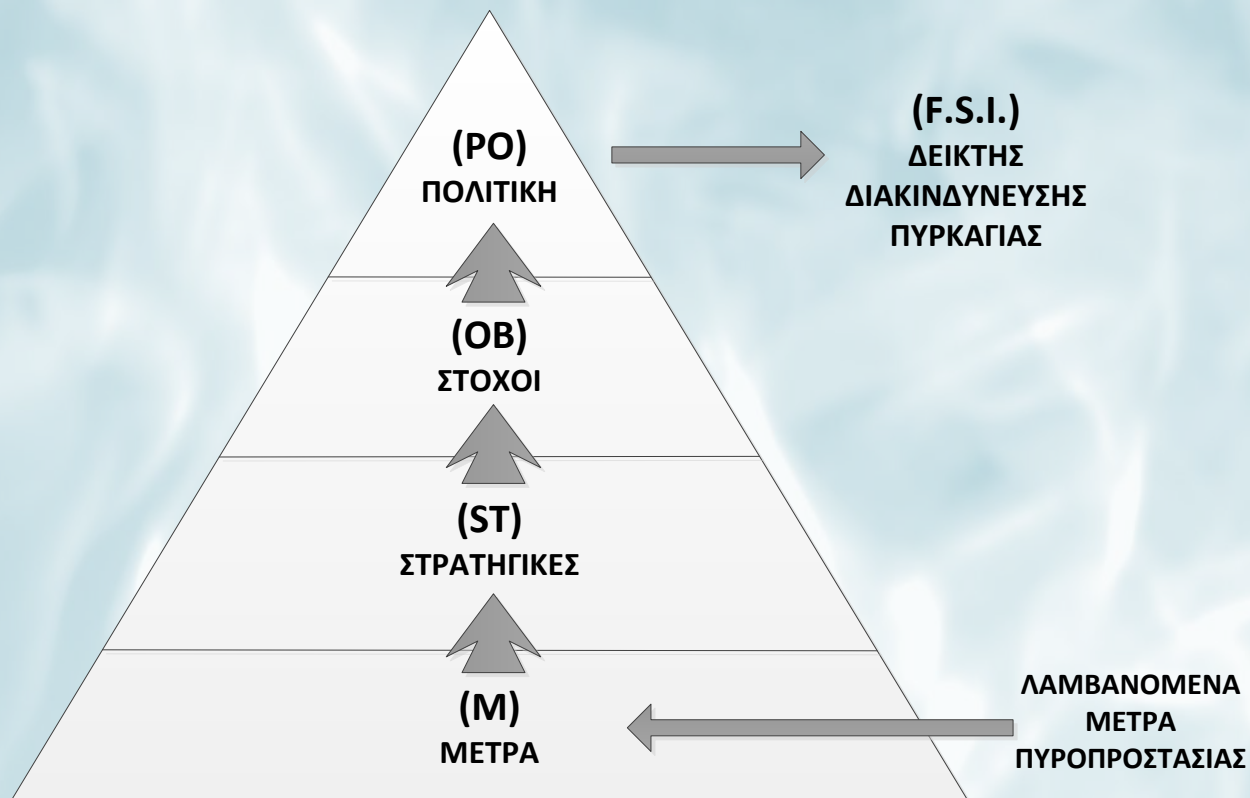




## Fire Risk Management

### Model of the optimized fire protection design

To upgrade the level of fire safety of a historic building while preserving, among other things, its authenticity



The structure of the hierarchy in the fire risk assessment



## Calculation of the Fire Safety Index (FSI)

### Model of the optimized fire protection design

To upgrade the level of fire safety of a historic building while preserving, among other things, its authenticity

$$FSI = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^p OB(i) \cdot ST(i, j) \cdot M(j, k) \cdot G(k)$$

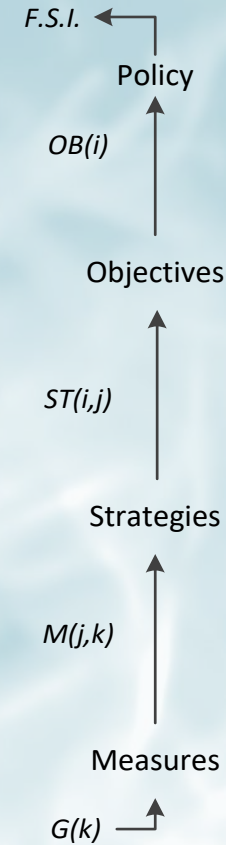
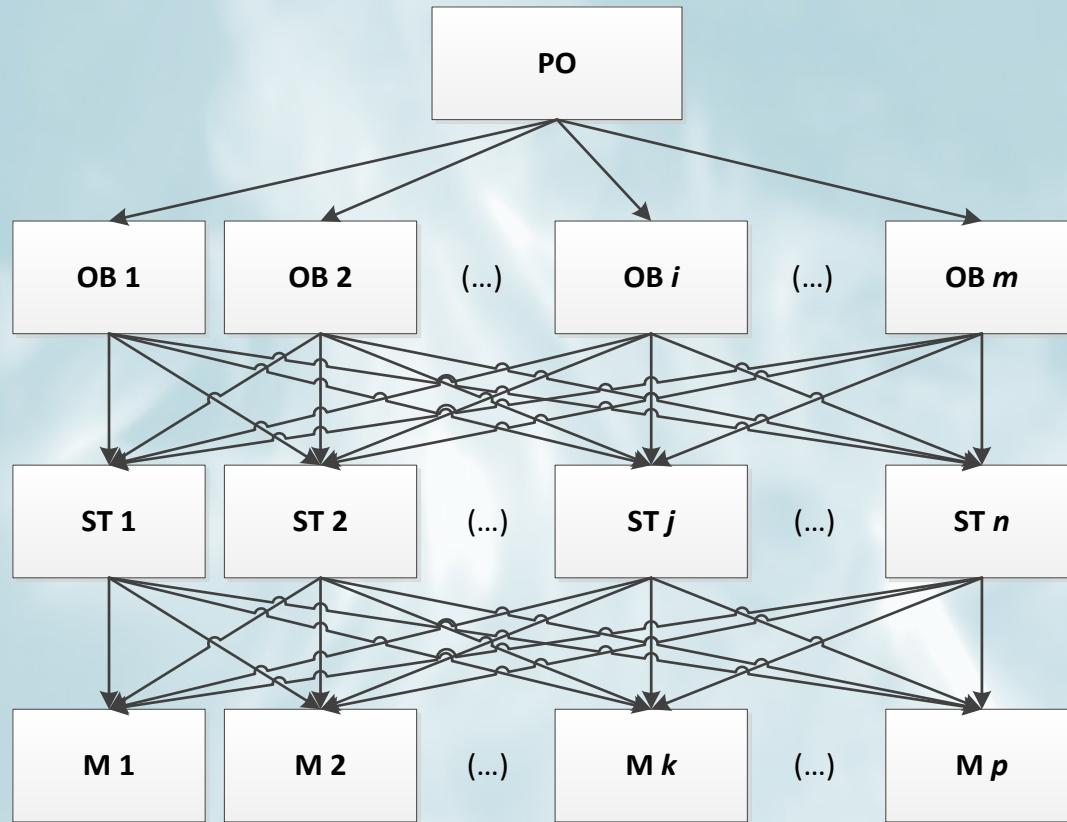
Where,

$$\begin{aligned} \sum_{i=1}^m OB(i) &= 1, \\ \sum_{j=1}^n ST(i, j) &= 1, \quad \forall i = 1, 2, \dots, m \\ \sum_{k=1}^p M(j, k) &= 1, \quad \forall j = 1, 2, \dots, n \end{aligned}$$

where,  $OB(i)$ ,  $ST(i, j)$  and  $M(j, k)$  represent the weight coefficients of  $OB_i$  objective in terms of the policy PO, the  $OB_i$  objective *and* the  $ST_j$  strategy, respectively. While  $G(k)$  expresses the grade of  $M_k$  measure implementation. Values of  $m$ ,  $n$  and  $p$  denote number of Objects, Strategies and Measures, respectively.



## Calculation of the FSI



Typical 4 levels AHP tree, incorporated to the present study to evaluate FSI

$$FSI = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^p OB(i) \cdot ST(i,j) \cdot M(j,k) \cdot G(k)$$





# Preserving Authenticity

## Case studies

### Villa Bianca



$FSI^{(initial)} = 0.48$

### Monastery of Simonos Petra



$FSI^{(initial)} = 0.53$

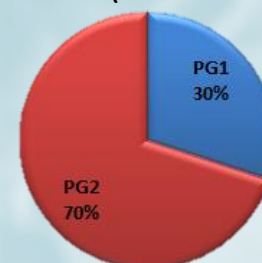


## Preserving Authenticity

### Assessment of Authenticity preservation (Villa Bianca)

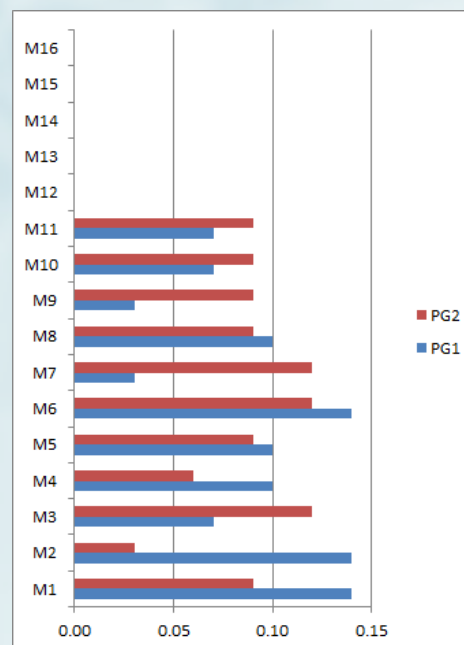
Weights (B) and normalized weights (K.B.) of 2 preservation objectives (POB1-POB2) with respect to preserving the cultural heritage (PPO)

PPO		PG1	PG2
		B	K.B.
	B	2	4
	K.B.	0.3	0.7



Weights (B) and normalized weights (K.B.) of the 16 measures (M1- M16) with respect to the 2 goals of authenticity (PG1-PG2).

	PG1		PG2	
	B.	K.B.	B.	K.B.
M1	4	0.14	3	0.09
M2	4	0.14	1	0.03
M3	2	0.07	4	0.12
M4	3	0.10	2	0.06
M5	3	0.10	3	0.09
M6	4	0.14	4	0.12
M7	1	0.03	4	0.12
M8	3	0.10	3	0.09
M9	1	0.03	3	0.09
M10	2	0.07	3	0.09
M11	2	0.07	3	0.09
M12	0	0.00	0	0.00
M13	0	0.00	0	0.00
M14	0	0.00	0	0.00
M15	0	0.00	0	0.00
M16	0	0.00	0	0.00





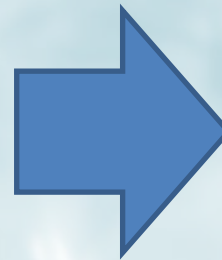
# Preserving Authenticity

## Model of the optimized fire protection design

To upgrade the level of fire safety of a historic building while preserving, among other things, its authenticity

### PROBLEM - SCENARIO

There is a historic building whose fire safety is to be improved to a certain level, with the least possible cost and with the least alteration of its authenticity.



### QUESTION

How to achieve the desired degree of fire safety with the least budget required and the least alteration of the authenticity of the building?

### PROBLEM - SCENARIO

There is a historic building that on the one hand aim to maximize fire safety, and on the other hand to minimize the intervention in the building, which is an alteration of its authenticity, under the limitation of the available funds (specific budget).



### QUESTION

How to distribute the available budget over the fire protection measures, in order to achieve the maximum possible fire safety and at the same time the minimum possible alteration of the authenticity of the building?





## Preserving Authenticity

### Formulations of the fire protection design optimization problem

Formulation A: Minimization of Cost and API  
subject to FSI constraint

Objective  
function



$$\begin{cases} \min C(G(k)) \\ \min \text{API}(G(k)) \end{cases}$$

Constraint



$$FSI \geq FSI_{\text{Target}}$$

#### Algorithms

- ATC
- NSGA-II

Formulation B: Minimization of API maximization of FSI  
subject to budget constraint

Objective  
function



$$\begin{cases} \max FSI(G(k)) \\ \min \text{API}(G(k)) \end{cases}$$

Constraint



$$C \leq C_{\text{Target}}$$

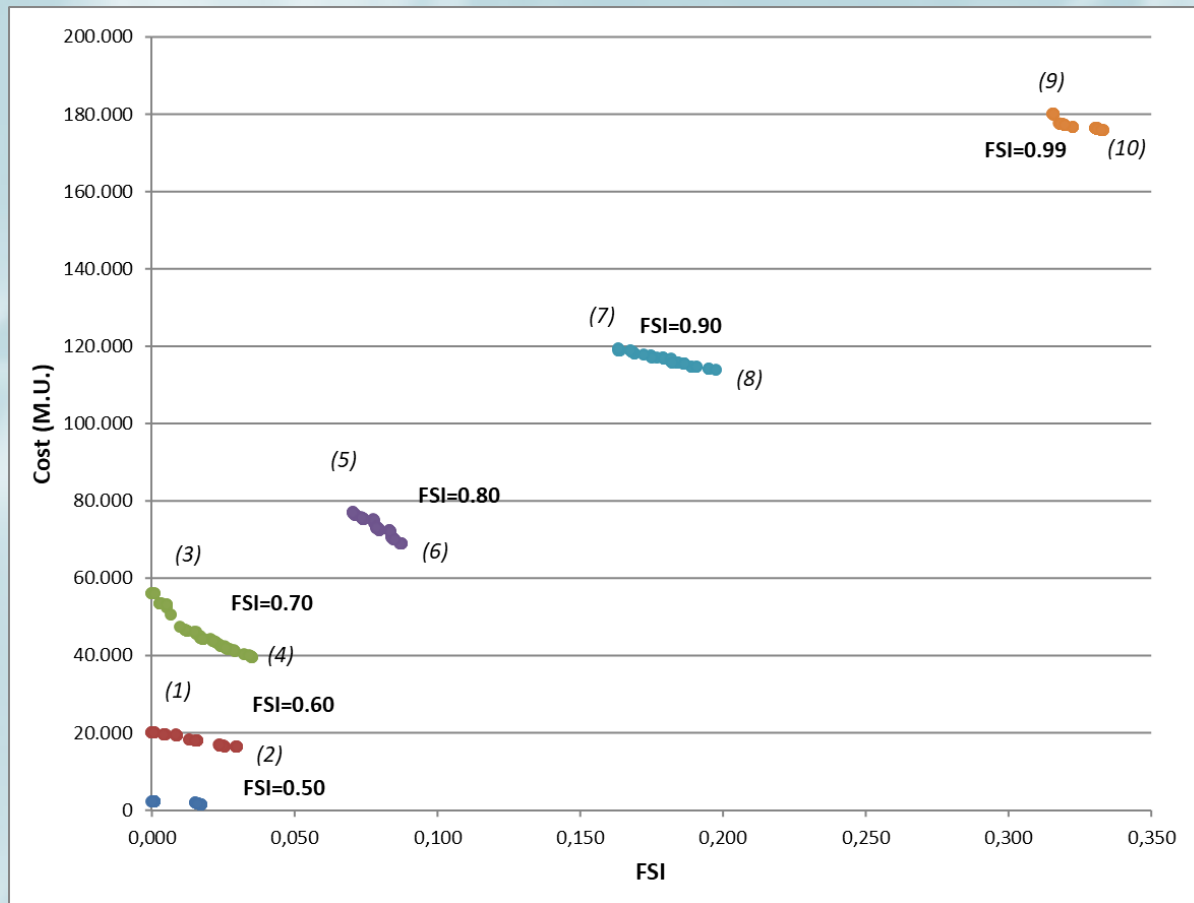
#### Algorithms

- ATC



# Preserving Authenticity

## NSGA-II – Villa Bianca - Formulation A



Presentation of Pareto fronts for the six test cases of FSI target value



## Preserving Authenticity

### NSGA-II – Villa Bianca - Formulation A

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
FSI(Target)	0.60	0.60	0.70	0.70	0.80	0.80	0.90	0.90	0.99	0.99
M1	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.56	0.96	0.96
M2	0.40	0.40	0.40	0.40	0.44	0.44	0.99	0.97	0.96	0.96
M3	0.70	0.98	0.70	0.98	0.98	0.99	0.99	1.00	1.00	1.00
M4	0.50	0.50	0.50	0.57	1.00	1.00	1.00	1.00	1.00	1.00
M5	0.80	0.80	0.80	0.80	0.80	0.80	0.86	0.98	0.99	0.99
M6	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.60	0.90
M7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.30	0.30
M8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M9	0.70	0.70	0.70	0.70	0.73	0.96	0.99	0.98	0.96	0.96
M10	0.60	0.60	0.60	0.60	0.60	0.60	0.99	0.97	1.00	0.99
M11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.69	0.44
M12	0.70	0.38	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M13	0.00	0.00	1.00	0.03	1.00	0.98	1.00	0.98	0.99	0.99
M14	1.00	0.94	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M15	0.50	0.50	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00
M16	0.20	0.20	0.87	0.20	0.98	0.20	0.97	0.20	0.76	0.76
API	0.00	0.03	0.00	0.04	0.07	0.09	0.16	0.20	0.32	0.33
Cost	20228	16343	56136	39495	77166	68858	119329	113872	180170	175950

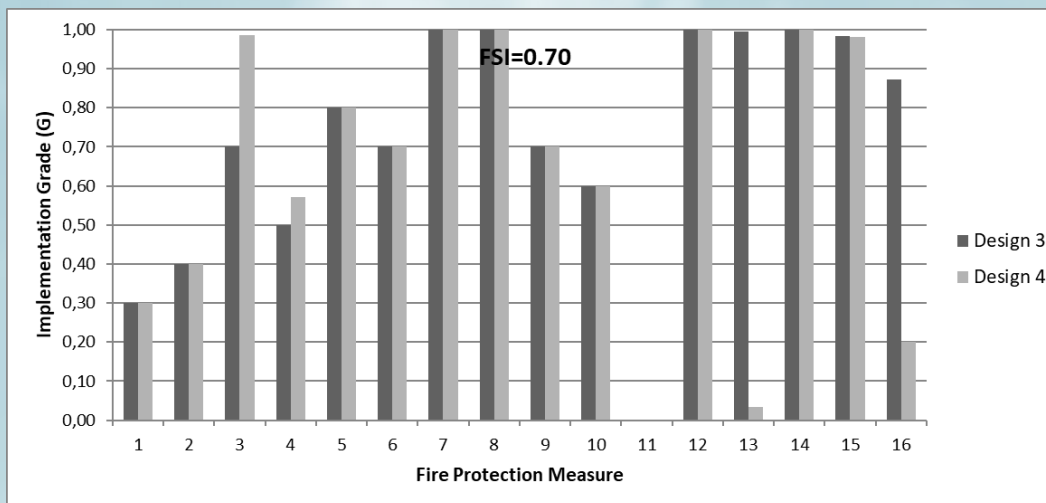
Optimized implementation grades of the 16 fire protection measures for the 10 denoted designs in the previous slide



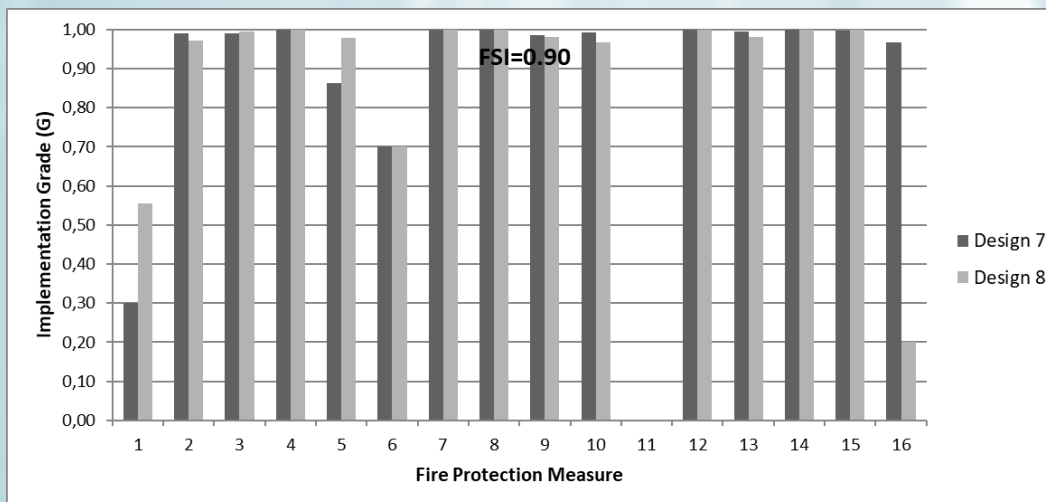


## Preserving Authenticity

### NSGA-II – Villa Bianca - Formulation A



Implementation grades of the 16 fire protection measures for designs (3) and (4) of the pareto front corresponding to FSI=0.70

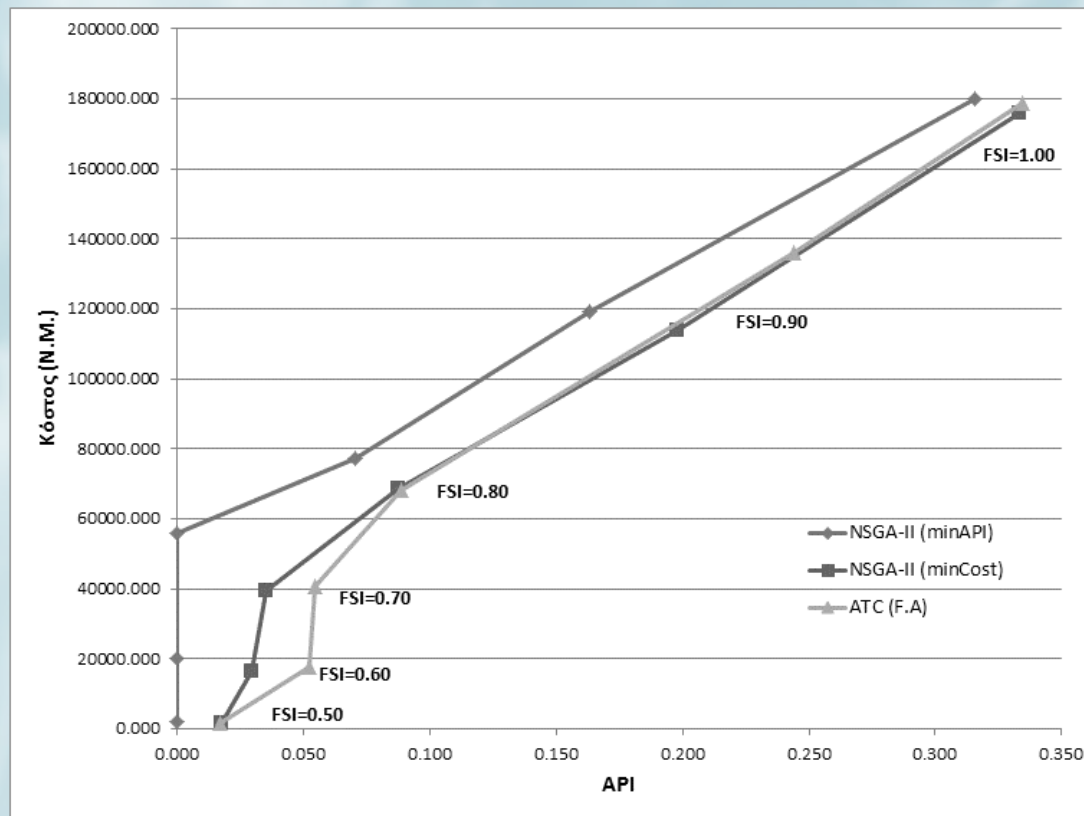


Implementation grades of the 16 fire protection measures for designs (7) and (8) of the pareto front corresponding to FSI=0.90



## Preserving Authenticity

### Comparison ATC vs NSGA-II – Villa Bianca



Results obtained by ATC (Formulation A) and NSGA-II approaches for the test case of Villa Bianca



## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation A

Measure	Cost per sq.m.	0.53	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	0.999
FSI Achieved			0.55	0.60	0.65	0.70	0.75	0.80	0.88	0.91	0.95	0.999
M 1	40	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.42	0.86	0.98	1.00
M 2	40	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.67	0.74	1.00	1.00
M 3	10	0.60	0.81	1.00	1.00	1.00	1.00	1.00	0.96	1.00	0.94	1.00
M 4	30	0.60	0.60	0.60	0.60	0.60	1.00	1.00	0.98	0.92	0.91	1.00
M 5	10	0.50	0.50	0.90	1.00	1.00	1.00	1.00	0.91	0.97	0.99	1.00
M 6	30	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.84	0.78	0.64	0.99
M 7	20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.78	0.71	0.90	1.00
M 8	10	0.20	0.20	0.20	0.79	1.00	1.00	1.00	0.90	0.99	1.00	1.00
M 9	30	0.60	0.60	0.60	0.60	0.60	0.69	0.99	1.00	0.81	0.99	1.00
M 10	40	0.50	0.50	0.50	0.50	0.50	0.50	0.55	0.94	0.97	0.99	1.00
M 11	40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.96	0.95	1.00
M 12	20	0.90	0.90	0.90	0.90	0.90	1.00	1.00	0.96	0.98	0.96	1.00
M 13	10	0.50	0.50	0.50	0.50	0.50	1.00	1.00	0.84	0.95	0.92	1.00
M 14	10	0.90	0.90	0.90	0.90	0.98	1.00	1.00	0.99	0.97	0.99	1.00
M 15	20	0.60	0.60	0.60	0.60	1.00	0.60	1.00	0.84	0.88	0.98	1.00
M 16	20	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.73	0.57	0.74	0.99
Cost---->>>		0.00	15049	55421	104984	180315	277370	409322	984505	1110830	1287804	1473340
API ----->>>>>		0.00	0.02	0.06	0.11	0.14	0.18	0.21	0.38	0.43	0.48	0.55

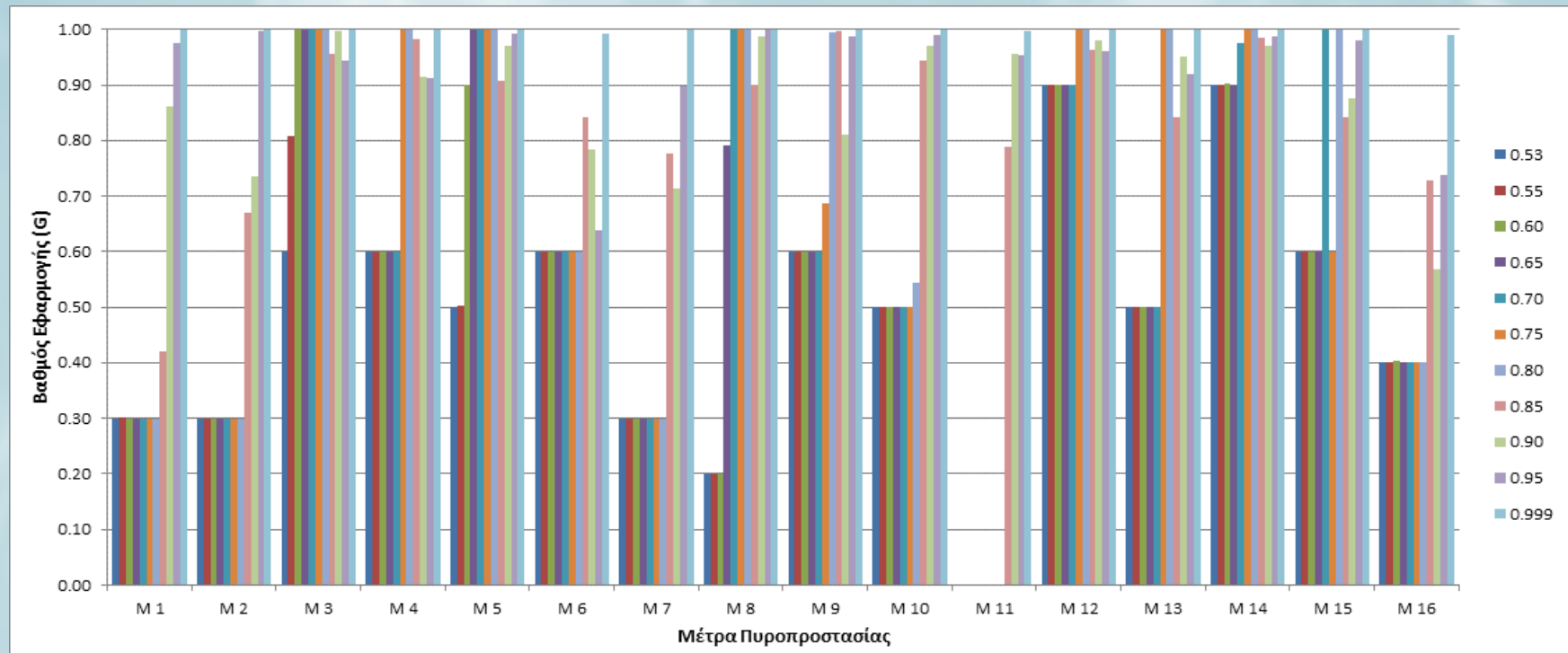
Optimized implementation grades of the 16 fire protection measures for the 10 different FSI targets (F.A)





## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation A

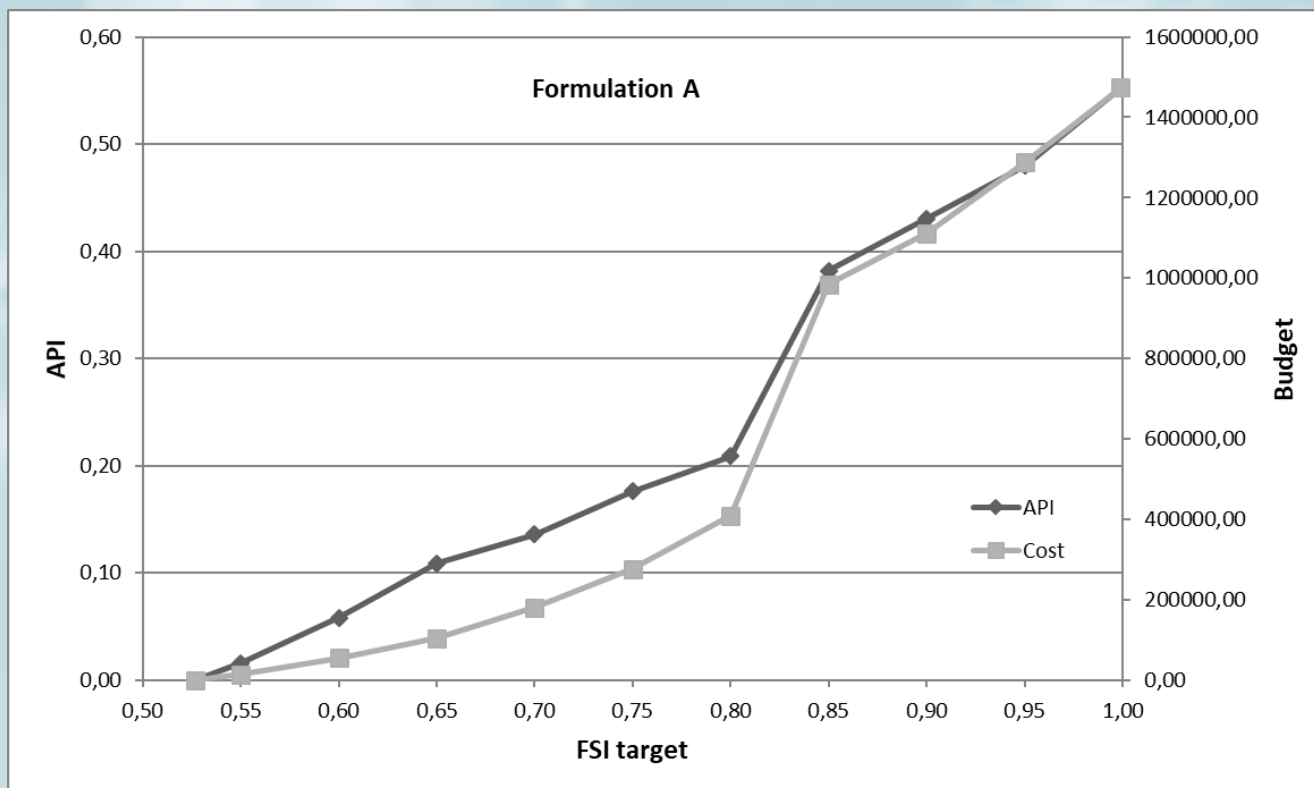


Optimized implementation grades of the 16 fire protection measures for the 10 different FSI targets (F.A)



## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation A



Cost and API representation for different FSI values



## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation B

Measure	Cost per sq.m.	0.00	150000	300000	450000	600000	750000	900000	1050000	1200000	1350000	1500000
Budget used		0.00	145156	237524	375194	565171	743845	886958	1032732	1173260	622736	654392
M 1	40	0.30	0.30	0.31	0.39	0.64	0.52	0.55	0.86	0.96	0.42	0.42
M 2	40	0.30	0.70	0.30	0.47	0.30	0.64	0.64	0.73	0.99	0.68	0.69
M 3	10	0.60	0.70	0.60	0.95	0.85	0.84	0.97	0.96	0.92	0.84	0.84
M 4	30	0.60	0.61	0.64	0.78	0.80	0.75	0.95	0.84	0.97	0.84	0.84
M 5	10	0.50	0.68	0.69	0.77	0.87	0.83	0.87	0.87	0.56	0.82	0.81
M 6	30	0.60	0.60	0.60	0.82	0.60	0.78	0.80	0.81	0.96	0.75	0.68
M 7	20	0.30	0.31	0.31	0.36	0.31	0.85	0.76	0.74	0.91	0.69	0.30
M 8	10	0.20	0.21	0.26	0.36	0.31	0.28	0.59	0.56	0.60	0.77	0.78
M 9	30	0.60	0.61	0.87	0.63	0.77	0.79	0.81	0.92	0.94	0.83	0.83
M 10	40	0.50	0.50	0.73	0.76	0.93	0.99	0.99	0.92	0.95	0.75	0.73
M 11	40	0.00	0.00	0.04	0.11	0.66	0.49	0.64	0.87	0.70	0.05	0.43
M 12	20	0.90	0.90	0.90	0.97	0.97	0.95	0.94	0.98	0.99	1.00	1.00
M 13	10	0.50	0.51	0.99	0.75	0.59	0.69	0.67	0.80	0.75	0.73	0.73
M 14	10	0.90	0.90	0.92	0.96	0.93	1.00	0.99	0.93	0.98	1.00	1.00
M 15	20	0.60	0.64	0.60	0.68	0.74	0.76	0.94	0.83	1.00	1.00	1.00
M 16	20	0.40	0.42	0.70	0.45	0.41	0.68	0.60	0.63	0.54	0.68	0.68
FSI		0.53	0.58	0.61	0.69	0.73	0.75	0.84	0.85	0.88	0.78	0.79
API		0	0.06	0.08	0.16	0.20	0.27	0.34	0.38	0.42	0.25	0.25

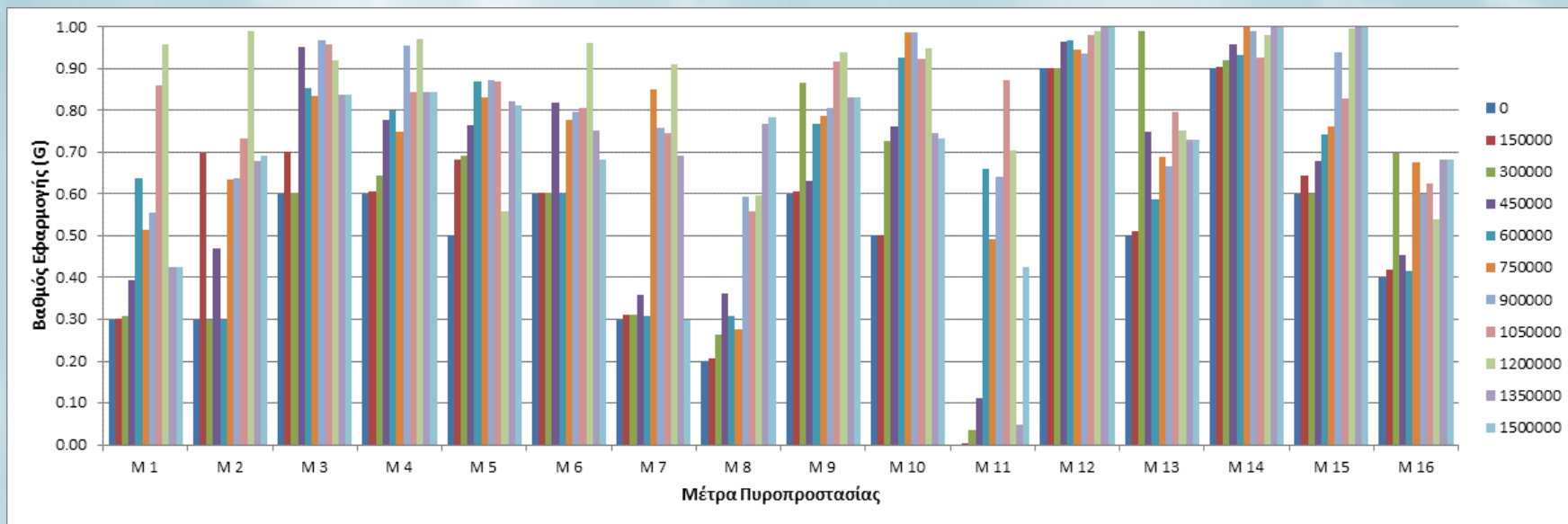
Optimized implementation grades of the 16 fire protection measures for the 10 different Cost targets (F.B)





## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation B

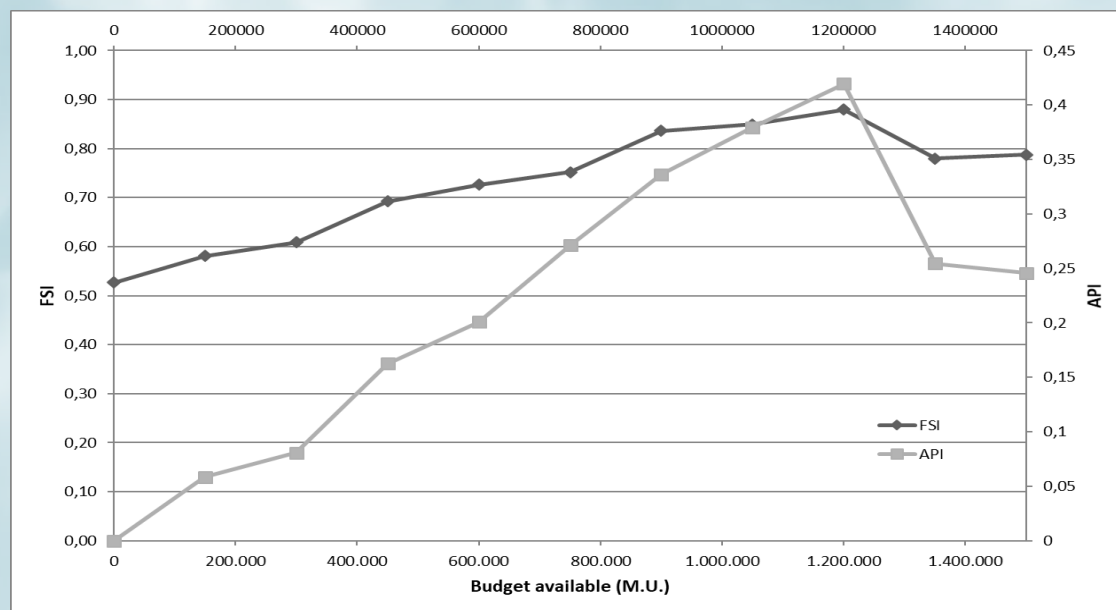


Optimized implementation grades of the 16 fire protection measures for the 10 different Cost targets (F.B)



## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation B

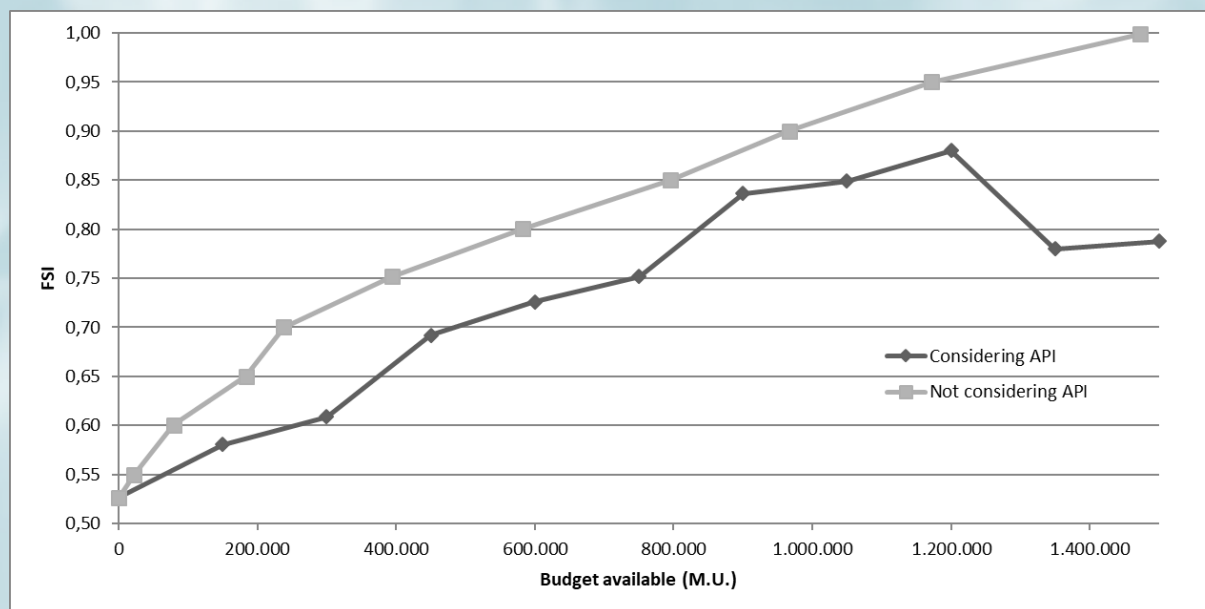


FSI and API for different budget available



## Preserving Authenticity

### ATC - Monastery of Simonos Petra - Formulation B



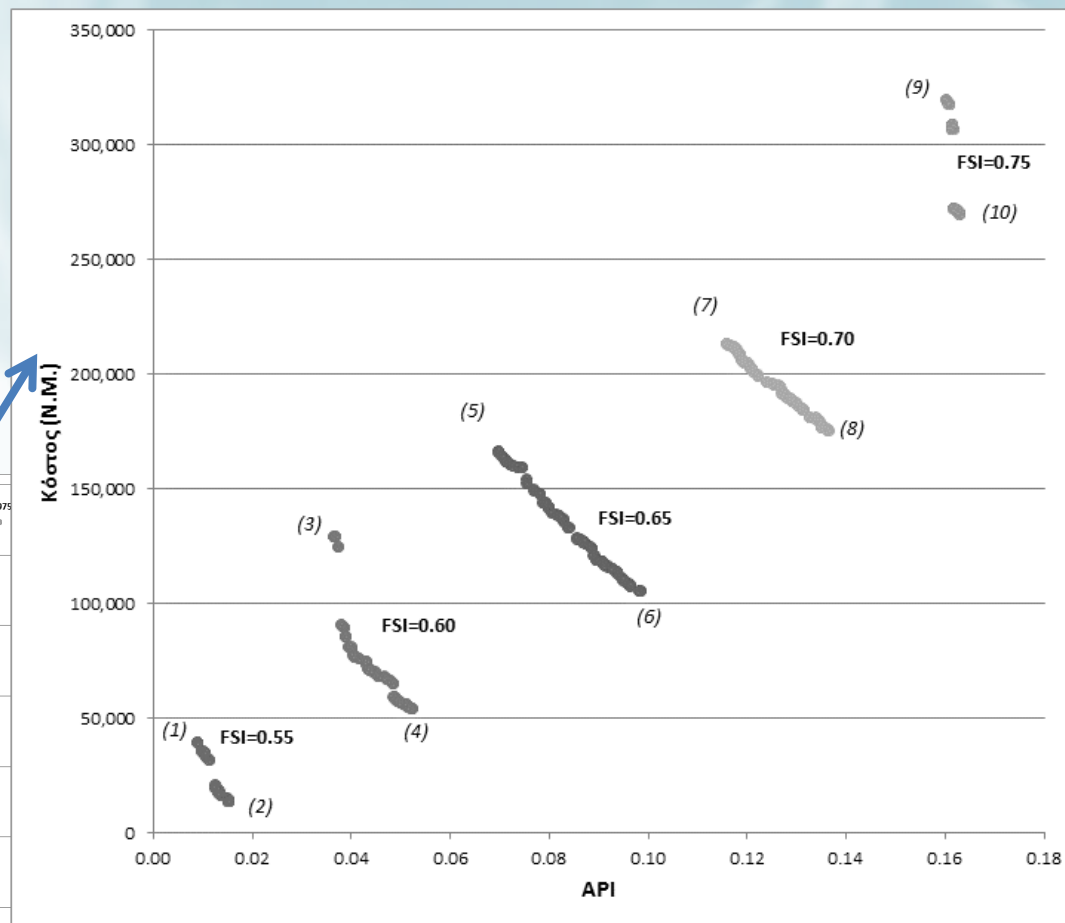
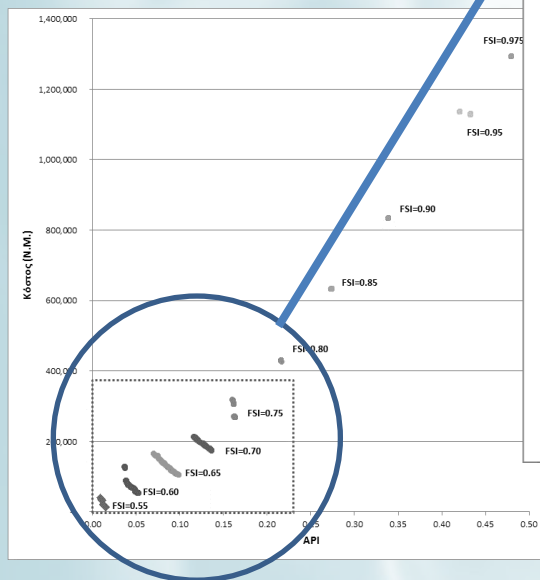
FSI for different budget available, considering and not considering authenticity preservation





## Preserving Authenticity

### NSGA-II - Monastery of Simonos Petra - Formulation A



Presentation of Pareto fronts for the 5 characteristic test cases of FSI target value



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### NSGA-II - Monastery of Simonos Petra - Formulation A

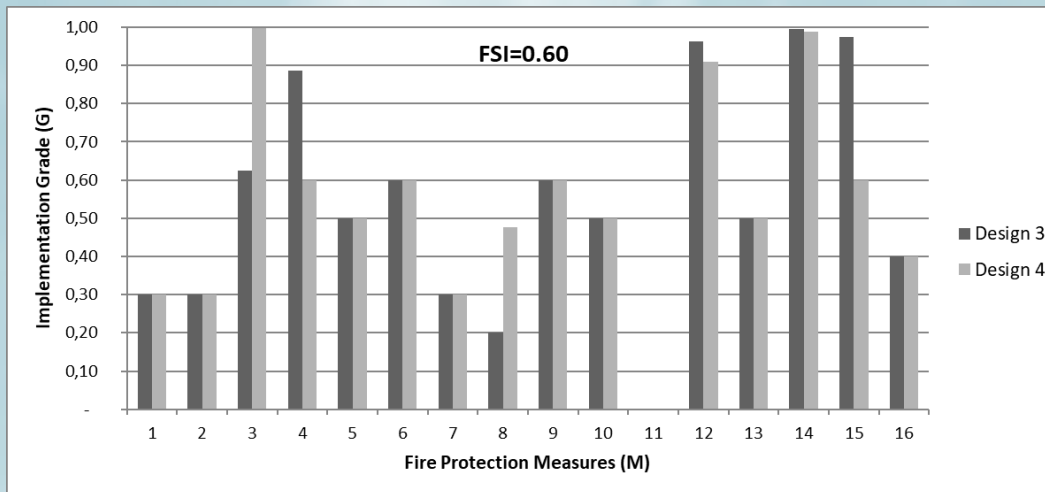
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
FSI (Target)	0.55	0.55	0.60	0.60	0.65	0.65	0.70	0.70	0.75	0.75
M1	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
M2	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
M3	0.63	0.80	0.62	1.00	0.99	1.00	1.00	1.00	1.00	1.00
M4	0.60	0.60	0.89	0.60	0.99	0.60	0.90	0.74	0.99	0.98
M5	0.50	0.50	0.50	0.50	0.50	0.70	0.54	0.95	0.63	0.98
M6	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
M7	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
M8	0.20	0.20	0.20	0.48	0.20	0.89	0.84	0.98	0.99	0.98
M9	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.87	0.61
M10	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.55	0.50
M11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M12	0.95	0.90	0.96	0.91	0.96	0.91	0.99	0.97	1.00	1.00
M13	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
M14	1.00	0.90	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00
M15	0.75	0.60	0.98	0.60	0.90	0.65	0.99	0.71	1.00	0.98
M16	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
API	0.01	0.02	0.04	0.05	0.07	0.10	0.12	0.14	0.16	0.16
Κόστος	39982	14109	129704	54594	167032	105756	213875	175719	319978	270172

Optimized implementation grades of the 16 fire protection measures for the 10 denoted designs denoted in the previous slide

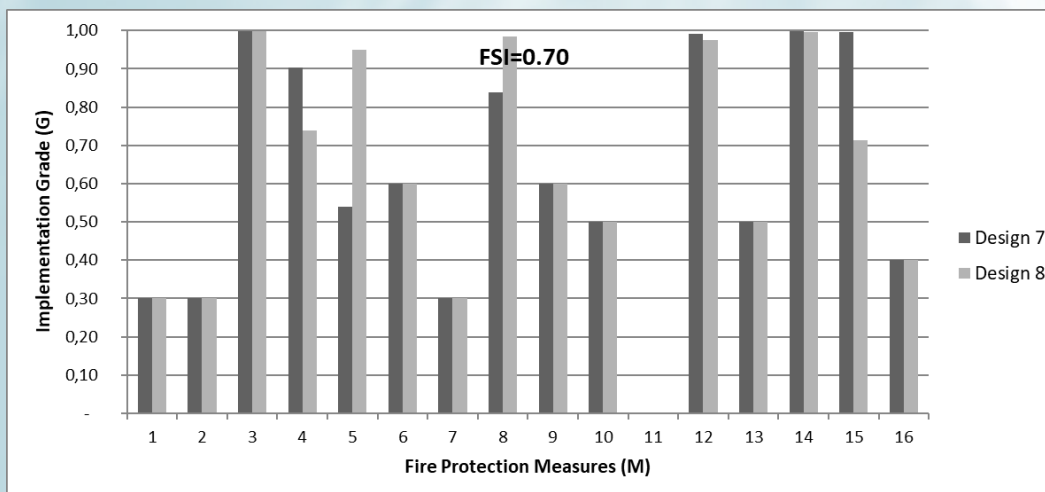


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### NSGA-II - Monastery of Simonos Petra - Formulation A



Implementation grades of the 16 fire protection measures for designs (3) and (4) of the pareto front corresponding to FSI=0.60



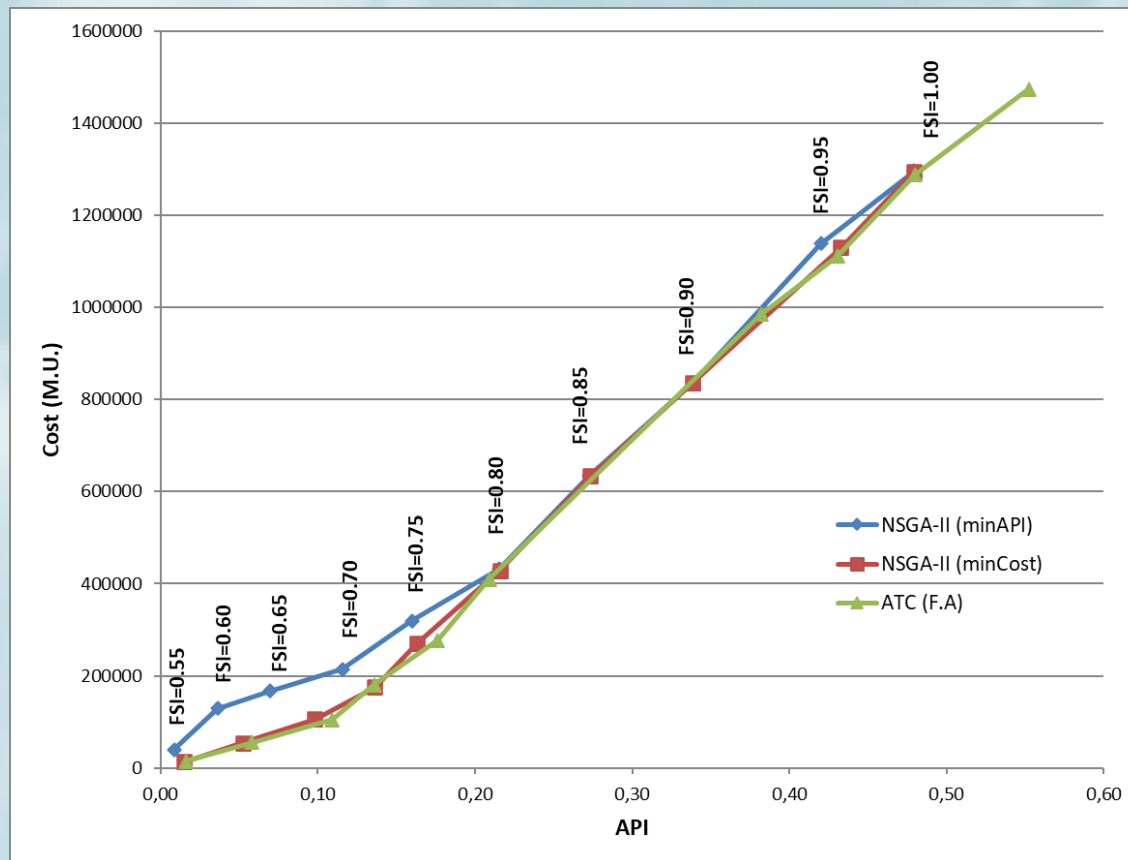
Implementation grades of the 16 fire protection measures for designs (7) and (8) of the pareto front corresponding to FSI=0.70





## Preserving Authenticity

### Comparison ATC vs NSGA-II – Monastery of Simonos Petra



Results obtained by ATC (Formulation A) and NSGA-II approaches for the test case of Monastery of Simonos Petra

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers”

...ὕψηλοκρήμνοις τὸν λεωργὸν ὀχμάσαι  
ἀδαμαντίνων δεσμῶν ἐν ἀρρήκτοις πέδαις.  
τὸ σὸν γὰρ ἄνθος, παντέχνου πυρὸς σέλας,  
θνητοῖσι κλέψας ὥπασεν. τοιᾶσδέ τοι  
ἁμαρτίας σφε δεῖ θεοῖς δοῦναι δίκην...

Αἰσχύλου Προμηθεὺς Δεσμώτης  
(Απόσπασμα από το προοίμιο όπου το Κράτος  
απευθύνεται στον Ἡφαίστο, στίχοι 5-9)

# THANK YOU FOR YOUR ATTENTION

...στα βράχια στους ψηλούς γκρεμούς να πεδικλώσεις  
μ' αλύσων ασύντριφτα δεσμά ατσαλένια,  
γιατί έκλεψε της πάντεχνης φωτιάς τη φλόγα,  
-τ' ἄνθος σου εσένα- και το χάρισε τ' ανθρώπου.  
Τέτοιο κρίμα χρωστάει λοιπόν να μας πλερώσει...

μετάφραση: Ι. Γρυπάρη

«Prometheus Bound»

Λάδι σε καμβά (1611-1618) - Peter Paul Rubens & Frans Snyders - Philadelphia Museum of Art