

# Contents

|  |              |
|--|--------------|
| <b>Resumen</b>   | <b>iii</b>   |
| <b>Resum</b>   | <b>v</b>     |
| <b>Abstract</b>  | <b>vii</b>   |
| <b>Acknowledgements</b>  | <b>ix</b>    |
| <b>Agradecimientos</b>   | <b>xiii</b>  |
| <b>Contents</b>  | <b>xvii</b>  |
| <b>List of Figures</b>   | <b>xxi</b>   |
| <b>List of Tables</b>  | <b>xxiii</b> |
| <b>1 Motivation and scope of the research</b>                        | <b>1</b>     |
| 1.1 Motivation of the research . . . . .                             | 2            |
| 1.1.1 Containerized maritime trade . . . . .                         | 2            |
| 1.1.2 The role of optimization at container port terminals . . . . . | 4            |
| 1.2 Scope . . . . .  | 5            |
| 1.3 Objectives . . . . .   | 6            |
| 1.3.1 More realistic formulations . . . . .                          | 6            |

|          |   |           |
|----------|---|-----------|
| 1.3.2    | A versatile solution method . . . . .                                   | 7         |
| 1.4      | Outline . . . . .   | 8         |
| 1.5      | Scientific contributions associated with this thesis . . . . .          | 11        |
| 1.5.1    | Published papers in international journals . . . . .                    | 11        |
| 1.5.2    | Papers in preparation . . . . .   | 11        |
| 1.5.3    | Oral presentations at international conferences . . . . .               | 12        |
| 1.5.4    | Oral presentations at Spanish national conferences . . . . .            | 13        |
| 1.5.5    | Oral presentations at workshops and seminars . . . . .                  | 13        |
| <b>2</b> | <b>Introduction</b>   | <b>15</b> |
| 2.1      | Optimization of port terminal operations . . . . .                      | 16        |
| 2.1.1    | Seaside operations . . . . .  | 17        |
| 2.1.2    | Yard operations . . . . .   | 17        |
| 2.1.3    | Landside operations . . . . .   | 18        |
| 2.2      | Literature review . . . . .   | 19        |
| 2.2.1    | Solving the Container Premarshalling Problem (CPMP) . . . . .           | 19        |
| 2.2.2    | Related problems . . . . .  | 22        |
| 2.3      | Constraint Programming . . . . .  | 24        |
| 2.3.1    | Constraint Satisfaction Problems . . . . .                              | 24        |
| 2.3.2    | Types of constraints . . . . .  | 26        |
| 2.3.3    | Particular cases and extensions of CSPs . . . . .                       | 27        |
| 2.3.4    | Search strategies . . . . .   | 29        |
| <b>3</b> | <b>A constraint programming approach for the premarshalling problem</b> | <b>33</b> |
| 3.1      | CPMP: The Container Premarshalling Problem . . . . .                    | 34        |
| 3.1.1    | Notation . . . . .  | 36        |
| 3.2      | Constraint programming models . . . . .                                 | 37        |
| 3.2.1    | CP2: Constraint programming model with 2 groups of variables . . . . .  | 38        |
| 3.2.2    | CP3: Constraint programming model with 3 groups of variables . . . . .  | 40        |
| 3.2.3    | CP4: Constraint programming model with 4 groups of variables . . . . .  | 43        |
| 3.2.4    | CP5: Constraint programming model with 5 groups of variables . . . . .  | 45        |
| 3.2.5    | Solution method . . . . .   | 47        |
| 3.3      | Computational experiments . . . . .                                     | 48        |
| 3.3.1    | Technical details of the experiments . . . . .                          | 49        |
| 3.3.2    | Size of the CP models . . . . .   | 50        |
| 3.3.3    | Performance of models CP2, CP3, CP4 and CP5 . . . . .                   | 51        |

|          |   |           |
|----------|---|-----------|
| 3.3.4    | Performance of the algorithm . . . . .  | 55        |
| 3.3.5    | Comparison with the state-of-the-art integer programming model<br>and between constraint programming and mathematical program-<br>ming approaches . . . . . | 56        |
| 3.4      | Concluding remarks . . . . .  | 60        |
| <b>4</b> | <b>Solving the premarshalling problem with an auxiliary bay</b>   | <b>61</b> |
| 4.1      | CPMP-AB: The Container Premarshalling Problem with an Auxiliary Bay .   | 62        |
| 4.1.1    | Notation . . . . .  | 66        |
| 4.2      | Constraint programming models for the CPMP-AB . . . . .   | 67        |
| 4.2.1    | AB: Model for premarshalling with an auxiliary bay . . . . .  | 67        |
| 4.2.2    | ABp: Alternative model with a penalty for inter-bay relocations . .   | 73        |
| 4.2.3    | Solution method . . . . .   | 74        |
| 4.3      | Computational experiments . . . . .   | 76        |
| 4.3.1    | Performance of the proposed models . . . . .  | 77        |
| 4.3.2    | Differences in the solutions when considering or not an auxiliary bay,<br>and when including or not a penalty for inter-bay relocations . . . .             | 78        |
| 4.4      | Concluding remarks . . . . .  | 80        |
| <b>5</b> | <b>Premarshalling problems considering crane times</b>  | <b>83</b> |
| 5.1      | CPMPCT: The Container Premarshalling Problem with Crane Time Mini-<br>mization Objective . . . . .  | 84        |
| 5.1.1    | Crane time specifications and notation . . . . .  | 85        |
| 5.2      | CPMP-LCT: The Container Premarshalling Problem under Limited Crane<br>Time . . . . .  | 87        |
| 5.2.1    | Partial premarshalling solutions . . . . .  | 90        |
| 5.3      | Constraint programming models for the CPMPCT and the CPMP-LCT . .   | 93        |
| 5.3.1    | MCT: A model for premarshalling minimizing crane time . . . . .   | 93        |
| 5.3.2    | LCT1: A model for premarshalling under limited crane time . . . .   | 99        |
| 5.3.3    | LCT2: An alternative model for bays where all container priorities<br>differ . . . . .  | 101       |
| 5.3.4    | Solution method . . . . .   | 102       |
| 5.4      | Computational experiments . . . . .   | 103       |
| 5.4.1    | Minimizing crane time: MCT vs IPCT . . . . .  | 104       |
| 5.4.2    | Performance of the proposed models for the CPMP-LCT: LCT1 and<br>LCT2 . . . . .   | 105       |

|          |  |            |
|----------|--|------------|
| 5.4.3    | Heuristic solutions in short times for the CPMP-LCT . . . . .  | 107        |
| 5.5      | Concluding remarks . . . . .   | 110        |
| <b>6</b> | <b>Alternative approaches for the premarshalling problem under limited crane time</b>                          | <b>111</b> |
| 6.1      | Alternative objectives for the CPMP-LCT . . . . .  | 112        |
| 6.2      | Constraint programming models and solution methods for the CPMP-LCT  | 117        |
| 6.2.1    | LCT-I: A model and a solution method for minimizing the inaccessible containers . . . . .                      | 117        |
| 6.2.2    | LCT-IB: A model and a solution method for minimizing the sum of inaccessible and blocking containers . . . . . | 121        |
| 6.2.3    | LCT-BRP: A model and a solution method for minimizing the relocations in the retrieval phase . . . . .         | 122        |
| 6.3      | A constraint programming model for the Block Relocation Problem . . . .  | 130        |
| 6.4      | Computational experiments . . . . .  | 134        |
| 6.4.1    | Performance of the proposed models and solution methods for the CPMP-LCT . . . . .                             | 135        |
| 6.4.2    | Differences in the solutions yielded by the three different objectives   | 136        |
| 6.5      | Concluding remarks . . . . .   | 138        |
| <b>7</b> | <b>Conclusions and future work</b>   | <b>141</b> |
| 7.1      | Reformulating unrealistic assumptions for the premarshalling problem . . .                                     | 142        |
| 7.1.1    | Using an auxiliary bay for premarshalling . . . . .  | 142        |
| 7.1.2    | Considering crane times and limited availability of the crane . . . .  | 143        |
| 7.1.3    | Future research lines toward a more realistic premarshalling formulation . . . . .                             | 145        |
| 7.2      | Constraint Programming: An effective and versatile solution method for premarshalling . . . . .                | 146        |
| 7.2.1    | Designing constraint programming models . . . . .  | 146        |
| 7.2.2    | A versatile and effective solution method . . . . .  | 147        |
| 7.2.3    | Future research lines from a solution method perspective . . . . .   | 148        |
|          | <b>Bibliography</b>  | <b>149</b> |