

A User's Guide to the NRConv Nurse Rostering Converter

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Version 2.2 (May 2018)

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Chapter 1. Introduction

This document describes NRConv, a program for converting instances of nurse rostering problems from various existing formats into a common XML format called XESTT.

In NRConv's view of the world, there are three kinds of models. They all model instances of nurse rostering problems, and solutions to those instances, but they do it in different ways.

A *source model* is one of the models (concretely, file formats) that NRConv converts. At present NRConv can convert four source models: the Curtois 'original instances' model, the first international nurse rostering competition model, the second international nurse rostering competition model, and the Curtois-Qu 2014 model. However, NRConv is designed to minimize the work needed to add new source models.

The *intermediate model*, also called the *NRC model* after the software platform that implements it, represents the concepts underlying source models, including metadata, days, shifts, cover, patterns, and so on. If something in some source model is not in the intermediate model, then either the intermediate model needs to be extended, or else the source model is beyond the scope of NRConv. The intermediate model also includes its own versions of the XESTT concepts of archive (a set of instances and solution groups) and solution group (a set of solutions). There is no file format for the intermediate model; its values are held only in memory.

Finally, there is the *target model*, XESTT. Its main concepts are archives, instances, times, resources, events, constraints, solution groups, and solutions. It lies in memory, in objects defined by the KHE platform which implements XESTT, and it also has a file format version. The user of NRConv does not need to be a KHE expert, because NRConv uses it only behind the scenes.

There are two parts to NRConv, a *platform* called NRC and the *converters*. NRC defines many types and functions, culminating in type `NRC_ARCHIVE`, representing a set of instances and a set of solution groups in the intermediate model, and function `NrcArchiveWrite`, which converts an `NRC_ARCHIVE` object into a target model archive and writes it by calling `KheArchiveWrite`.

Each converter is a function which reads instance and solution files in one source model and converts what it reads into intermediate model objects. Since the intermediate model understands all the source model concepts, this conversion should be straightforward, a matter of reading the source model file and generating calls to the NRC platform. After this is done, the converter completes the conversion to the target model by calling `NrcArchiveWrite`.

NRConv is written in C, and is packaged with the author's KHE distribution, which is a gzipped tar file. To install it you need to get that file, unzip it, untar it, modify `makefile` slightly to say where you want the final `nrconv` binary to be copied to, and run `make`. After compiling, execute the `nrconv` binary with no command line options to get a comprehensive usage message.

Part A

The NRC Nurse Rostering Model

Chapter 2. NRC Archives and Solution Groups

The subject of this part is the NRC nurse rostering model. As explained in the introduction, the NRC model is an intermediate model, lying between the source models, which are existing nurse rostering models such as the First International Timetabling Competition model, and the target model, XESTT. By calling the functions defined in this part, a converter can convert instances and solutions in its model into the intermediate model; and then one call on `NrcArchiveWrite` converts that into XESTT and writes it as an XESTT archive.

This chapter describes types `NRC_ARCHIVE` and `NRC_SOLN_GROUP`, representing archives (sets of instances and solution groups) and solution groups (sets of solutions) in the intermediate model. Nurse rostering data formats do not seem to have features for grouping instances and solutions, beyond, say, the use of a zip file containing several instances. So these features of NRC are copied directly from the corresponding XESTT features.

2.1. Archives

An archive is a collection of instances together with groups of solutions to those instances. There may be any number of instances and solution groups. To create a new, empty archive, call

```
NRC_ARCHIVE NrcArchiveMake(char *id, HA_ARENA_SET as);
```

Here `id` is an identifier for the archive, and `as` is an arena set, used to gain efficient access to heap memory. You can safely pass `NULL` for arena set; to find out how to pass a non-`NULL` value, and why you might want to do that, read the KHE User's Guide. Function

```
char *NrcArchiveId(NRC_ARCHIVE archive);
```

returns the `Id` attribute.

Archive metadata may be set and retrieved by calling

```
void NrcArchiveSetMetaData(NRC_ARCHIVE archive, char *name,  
    char *contributor, char *date, char *description, char *remarks);  
void NrcArchiveMetaData(NRC_ARCHIVE archive, char **name,  
    char **contributor, char **date, char **description, char **remarks);
```

where `remarks`, being optional, may be `NULL`.

Initially an archive contains no instances and no solution groups. Solution groups are added automatically as they are created, because every solution group lies in exactly one archive. An instance may be added to an archive by calling

```
bool NrcArchiveAddInstance(NRC_ARCHIVE archive, NRC_INSTANCE ins);
```

`NrcArchiveAddInstance` returns `true` if it succeeds in adding `ins` to `archive`, and `false` otherwise, which can only be because `archive` already contains an instance with the same `Id` as `ins`. The instance will appear after any instances already present. An instance may be deleted from an archive (but not destroyed) by calling

```
void NrcArchiveDeleteInstance(NRC_ARCHIVE archive, NRC_INSTANCE ins);
```

`NrcArchiveDeleteInstance` aborts if `ins` is not in `archive`. If there are any solutions for `ins` in `archive`, they are deleted too. The gap left by deleting the instance is filled by shuffling subsequent instances up one place.

To visit the instances of an archive, call

```
int NrcArchiveInstanceCount(NRC_ARCHIVE archive);
NRC_INSTANCE NrcArchiveInstance(NRC_ARCHIVE archive, int i);
```

The first returns the number of instances in `archive`, and the second returns the `i`'th of those instances, counting from 0 as usual in C. There is also

```
bool NrcArchiveRetrieveInstance(NRC_ARCHIVE archive, char *id,
    NRC_INSTANCE *ins);
```

If `archive` contains an instance with the given `id`, this function sets `ins` to that instance and returns `true`; otherwise it leaves `*ins` untouched and returns `false`. In the same way,

```
int NrcArchiveSolnGroupCount(NRC_ARCHIVE archive);
NRC_SOLN_GROUP NrcArchiveSolnGroup(NRC_ARCHIVE archive, int i);
bool NrcArchiveRetrieveSolnGroup(NRC_ARCHIVE archive, char *id,
    NRC_SOLN_GROUP *soln_group);
```

visit the solution groups of an archive, and retrieve a solution group by `id`.

2.2. Solution groups

A solution group is a set of solutions to instances of its archive. To create a solution group, call

```
bool NrcSolnGroupMake(NRC_ARCHIVE archive, char *id,
    NRC_SOLN_GROUP *soln_group);
```

Parameter `archive` is compulsory. The solution group will be added to the archive. Parameter `id` is an identifier for the solution group. If the operation is successful, then `true` is returned with `*soln_group` set to the new solution group; if it is unsuccessful (which can only be because `id` is already the `Id` of a solution group of `archive`), then `false` is returned with `*soln_group` set to `NULL`. To retrieve these attributes, call

```
NRC_ARCHIVE NrcSolnGroupArchive(NRC_SOLN_GROUP soln_group);
char *NrcSolnGroupId(NRC_SOLN_GROUP soln_group);
```

Solution group metadata may be set and retrieved by calling


```

void NrcSolnGroupSetMetaData(NRC_SOLN_GROUP soln_group,
    char *contributor, char *date, char *description, char *publication,
    char *remarks);
void NrcSolnGroupMetaData(NRC_SOLN_GROUP soln_group,
    char **contributor, char **date, char **description, char
**publication,
    char **remarks);

```

where `publication` and `remarks`, being optional, may be `NULL`.

Initially a solution group has no solutions. These are added and deleted by calling

```

void NrcSolnGroupAddSoln(NRC_SOLN_GROUP soln_group, NRC_SOLN soln);
void NrcSolnGroupDeleteSoln(NRC_SOLN_GROUP soln_group, NRC_SOLN soln);

```

A solution can only be added when its instance lies in the solution group's archive.

To visit the solutions of a solution group, call

```

int NrcSolnGroupSolnCount(NRC_SOLN_GROUP soln_group);
NRC_SOLN NrcSolnGroupSoln(NRC_SOLN_GROUP soln_group, int i);

```

Solutions have no `Ids`, so there is no `NrcSolnGroupRetrieveSoln` function. When solution `i` is deleted, `NrcSolnGroupSolnCount` decreases by 1, solution `i+1` becomes solution `i`, and so on.

2.3. Writing archives

To convert an archive to XESTT format and write it to a file, call

```

void NrcArchiveWrite(NRC_ARCHIVE archive, bool with_reports, FILE *fp);

```

File `fp` must be open for writing UTF-8 characters, and it remains open after the call returns. If `with_reports` is `true`, each written solution contains a `Report` section evaluating the solution. The initial tag will be `<EmployeeScheduleArchive>`.

`NrcArchiveWrite` converts the NRC archive into a KHE archive and writes that archive using `KheArchiveWrite`.

At present, NRC does not check that the names of its entities are distinct. If two entities with conflicting names are given to NRC, they will be accepted at the time, but `NrcArchiveWrite` will exit with an error message when the KHE conversion reports the problem.

Chapter 3. NRC Instances and Solutions

An *instance* is a particular case of the nurse rostering problem, for a particular ward and a particular period of time. A *solution* is a solution to a particular instance, saying which workers to assign to which shifts. This chapter describes the `NRC_INSTANCE` and `NRC_SOLN` data types, which represents instances and solutions as defined by the NRC model.

3.1. Overview

NRC instances contain days, shifts, workers, and constraints (unlike KHE instances, which contain times, resources, events, and constraints). These data types are strongly interconnected, so we begin by giving informal definitions of most of them, as an overview.

`NRC_INSTANCE` represents one *instance* of the nurse rostering problem: one case of it, for a particular hospital ward and a particular interval of time.

`NRC_DAY` represents one *day*: not a generic day like ‘Friday’, but a particular day like ‘Friday 18 November 2016’, although its calendar date need not be known to the instance.

`NRC_DAY_SET` represents one *day-set*, which is a set (actually a sequence) of days. An example of a day-set is the *cycle*, containing all the days of the instance.

`NRC_DAY_SET_SET` represents one *day-set set*: a set (again, actually a sequence) of day-sets. An example of a day-set set is the one containing one day-set for each day of the week. Its first day-set contains all the Sundays, its second contains all the Mondays, and so on.

`NRC_SHIFT_TYPE` represents a *shift type*: a generic shift like the day shift or night shift.

`NRC_SHIFT_TYPE_SET` represents a *shift-type set*: a set of shift types.

`NRC_SHIFT` represents a *shift*, which is a particular shift such as the night shift on 18 November 2016. Each shift is characterised by a day plus a shift type.

`NRC_SHIFT_SET` represents a *shift-set*: a set of shifts. For example, the shifts whose day is 18 November 2016 form a shift-set, as do the shifts whose shift type is the night shift.

`NRC_SHIFT_SET_SET` represents a *shift-set set*, which is a set of shift-sets.

`NRC_WORKER` represents one *worker*, NRC’s term for a nurse or employee.

`NRC_WORKER_SET` represents one *worker-set*: a set of workers. The leading examples of worker-sets are the sets of workers that share a particular contract, and the sets of workers that share a particular skill. Indeed, contracts and skills are represented in NRC by worker-sets.

`NRC_WORKER_SET_SET` represents one *worker-set set*: a set of worker-sets. For example, the set of all contracts is a worker-set set.

`NRC_WORKER_SET_TREE` is a tree of worker-sets, where children are subsets of their parents, and siblings are disjoint. It is used when analysing overlapping cover requirements.

`NRC_DEMAND` represents one *demand*, describing a demand for one worker made by a shift, including the penalty for when a worker is not assigned, and the default penalty to apply when a worker without the appropriate skill is assigned. One shift may have any number of demands.

`NRC_DEMAND_SET` represents one *demand-set*, a set of demands. One can add a demand-set to a shift, which is the same as adding each of its demands separately, only more convenient.

`NRC_POLARITY` is used by patterns and constraints to say that what counts about a shift-set is whether a worker is busy for at least one of its shifts, or free for all of them.

`NRC_PATTERN` represents a *pattern*: a sequence of shift-sets, each with a polarity. A pattern may be used to define a worker constraint which, for example, applies a penalty when the pattern appears within a worker's timetable.

`NRC_CONSTRAINT` represents one *worker constraint*: a rule about what a worker may do, which if broken in some solution adds a penalty to that solution's cost.

`NRC_SOLN` represents one *solution*: a collection of assignments to the demands of the shifts of one instance.

3.2. Debug functions

Many of NRC's entities have functions included to help with debugging. These functions all work in the same way. Their interface has this form:

```
void NrcEntityDebug(NRC_ENTITY e, int indent, FILE *fp);
```

where `NRC_ENTITY` stands for an NRC type like `NRC_SHIFT`, `NRC_WORKER`, and so on. This produces a debug print of `e` onto file `fp`, which must be open for writing 8-bit characters.

If `indent >= 0`, the print will be indented `indent` spaces and occupy one or more complete lines (that is, it will end with a newline). One debug function often calls another, in which case it adds 2 to the indent, producing a neatly formatted result.

If `indent < 0`, the print will not be indented and will contain no newlines. It will usually be abbreviated, perhaps by printing just the object's name rather than its contents.

3.3. Instance objects

This section describes instance objects: how to create them, and how to visit their components. (Whenever NRC makes an object that is part of an instance, that object is not only created and returned to the user, it is also added to the instance. So one can visit every object via functions on the instance.) Operations for creating components appear in later sections.

3.3.1. Creation, metadata, and archives

To make a new, empty instance, call

```
NRC_INSTANCE NrcInstanceMake(char *id, char *workers_word,
    HA_ARENA_SET as);
```

Parameter `id` is an identifier identifying the instance, returned by

```
char *NrcInstanceId(NRC_INSTANCE ins);
```

Parameter `workers_word` is the name to give to the single XESTT resource type. Good choices

are "Workers", "Nurses", "Employees", and so on. Parameter `as` may be `NULL`, or it may be an arena set, as for `NrcArchiveMake`; indeed, it would almost certainly be the same arena set.

NRC needs to know what penalty is wanted when a worker is assigned twice to the same shift. The default value is

```
NrcPenalty(true, 1, NRC_COST_FUNCTION_LINEAR, ins)
```

which, as Section 3.9.1 explains, makes avoiding clashes a hard constraint with weight 1.¹ If this is not correct for some reason, it can be changed, and the value retrieved, by

```
void NrcInstanceSetAvoidClashesPenalty(NRC_INSTANCE ins, NRC_PENALTY p);
NRC_PENALTY NrcInstanceAvoidClashesPenalty(NRC_INSTANCE ins);
```

There is also

```
NRC_PENALTY NrcInstanceZeroPenalty(NRC_INSTANCE ins);
```

which is a convenient way to obtain a penalty with weight 0.

Instance metadata may be set and retrieved by calling

```
void NrcInstanceSetMetaData(NRC_INSTANCE ins, char *name,
    char *contributor, char *date, char *country, char *description,
    char *remarks);
void NrcInstanceMetaData(NRC_INSTANCE ins, char **name,
    char **contributor, char **date, char **country, char **description,
    char **remarks);
```

where `remarks`, being optional, may be `NULL`.

For the convenience of functions that reorganize archives, an instance may lie in any number of archives. To add an instance to an archive and delete it from an archive, call functions `NrcArchiveAddInstance` and `NrcArchiveDeleteInstance` from Section 2.1. To visit the archives containing a given instance, call

```
int NrcInstanceArchiveCount(NRC_INSTANCE ins);
NRC_ARCHIVE NrcInstanceArchive(NRC_INSTANCE ins, int i);
```

in the usual way.

3.3.2. Day names, days, day-sets, and day-set sets

By default, the seven days of the week have their usual English names. To change this, call

```
void NrcInstanceSetDayNames(NRC_INSTANCE ins, char *short_names,
    char *long_names);
```

¹When a constraint which limits a worker to a most one shift per day is added, what it actually does is limit the number of times during that day when the worker may be busy to one. A worker who is assigned twice to the same shift is still only busy for one time, so NRC must generate a separate constraint, called an avoid clashes constraint, which prevents this. It does this without being asked, using this penalty for the constraint's penalty.

The first parameter contains the short names of the seven days, separated by colons, and beginning with the name of Sunday (which is how the Unix `mktime` function does it). The second parameter is the same except that it contains long names. For example, the call

```
NrcInstanceSetDayNames( ins, "Sun:Mon:Tue:Wed:Thu:Fri:Sat",
    "Sunday:Monday:Tuesday:Wednesday:Thursday:Friday:Saturday" );
```

does not need to be made, because it sets the day names to their default values.

Do not try to use `NrcInstanceResetDayNames` to begin the cycle on a day of the week other than Sunday. Setting parameter `first_day_index` of `NrcCycleMake` (Section 3.4) to a value other than 0 is the right way to do that.

To retrieve the day names, use

```
int NrcInstanceDayNameCount(NRC_INSTANCE ins);
char *NrcInstanceShortDayName(NRC_INSTANCE ins, int i);
char *NrcInstanceLongDayName(NRC_INSTANCE ins, int i);
```

The first day name (the one for Sunday) has index 0, the second (for Monday) has index 1, and so on. `NrcInstanceDayNameCount` always returns 7.

The day objects created make up a day-set called the *cycle*. For visiting them, see Section 3.3.3 below. To visit all the day-sets created within an instance, including the cycle, use

```
int NrcInstanceDaySetCount(NRC_INSTANCE ins);
NRC_DAY_SET NrcInstanceDaySet(NRC_INSTANCE ins, int i);
```

The day-sets are numbered from 0, so the code for visiting them all is

```
for( i = 0; i < NrcInstanceDaySetCount( ins ); i++ )
{
    ds = NrcInstanceDaySet( ins, i );
    ... visit ds ...
}
```

This is a standard arrangement throughout NRC. Similarly, call

```
int NrcInstanceDaySetSetCount(NRC_INSTANCE ins);
NRC_DAY_SET_SET NrcInstanceDaySetSet(NRC_INSTANCE ins, int i);
```

to visit all the day-set sets created within `ins`.

3.3.3. The cycle and the days of the week

The *cycle* (the sequence of all the days of the instance) is a day-set stored in the instance. Once a cycle has been added, by calling `NrcCycleMake` or `NrcCalendarCycleMake` (Section 3.4.2), the following operations become available. To retrieve the entire cycle as a day-set, call

```
NRC_DAY_SET NrcInstanceCycle(NRC_INSTANCE ins);
```

To visit the days in chronological order, call

```
int NrcInstanceCycleDayCount(NRC_INSTANCE ins);
NRC_DAY NrcInstanceCycleDay(NRC_INSTANCE ins, int i);
```

`NrcInstanceCycleDayCount` returns the number of days, and `NrcInstanceCycleDay` returns the *i*'th day. As usual in NRC, counting starts from 0, so the code to visit each day is

```
for( i = 0; i < NrcInstanceCycleDayCount(ins); i++ )
{
    day = NrcInstanceCycleDay(ins, i);
    ... visit day ...
}
```

There is also

```
bool NrcInstanceCycleRetrieveDay(NRC_INSTANCE ins, char *ymd,
    NRC_DAY *d);
```

which retrieves a day from the cycle by its calendar date. If the cycle contains a day whose year-month-day name is *ymd*, this function sets **d* to one such day and returns `true`; if not, it sets **d* to `NULL` and returns `false`. The date string must contain three non-negative integers separated by hyphens; a copy, normalized to a four-digit year and two-digit month and day, is used when retrieving.

At the same time a cycle is added to an instance, day-sets representing the 7 days of the week are also added. These are stored in a day-set set, and may be retrieved in that form by

```
NRC_DAY_SET_SET NrcInstanceDaysOfWeek(NRC_INSTANCE ins);
```

They may also be visited individually by calling

```
int NrcInstanceDaysOfWeekDaySetCount(NRC_INSTANCE ins);
NRC_DAY_SET NrcInstanceDaysOfWeekDaySet(NRC_INSTANCE ins, int i);
```

`NrcInstanceDaysOfWeekDaySetCount` returns the number of day-sets representing days of the week (always 7), and `NrcInstanceDaysOfWeekDaySet` returns the *i*'th of these day-sets, counting from 0 as usual. There is also

```
bool NrcInstanceDaysOfWeekRetrieveDaySet(NRC_INSTANCE ins,
    char *long_name, NRC_DAY_SET *ds);
```

which retrieves one of these day sets by long name. Irrespective of how the cycle was created, the first of these day-sets holds the Sunday days, the second holds the Monday days, and so on.

3.3.4. Shift types and shift-type sets

Functions for creating and querying shift types and shift-type sets are given in Section 3.6. To retrieve all the shift types of the instance as a shift-type set, call

```
NRC_SHIFT_TYPE_SET NrcInstanceAllShiftTypes(NRC_INSTANCE ins);
```

To visit the shift types of an instance one by one, call

```
int NrcInstanceShiftTypeCount(NRC_INSTANCE ins);
NRC_SHIFT_TYPE NrcInstanceShiftType(NRC_INSTANCE ins, int i);
```

counting from 0 in the usual way. To retrieve a shift type by name, call

```
bool NrcInstanceRetrieveShiftType(NRC_INSTANCE ins, char *name,
    NRC_SHIFT_TYPE *st);
```

As usual, if there is a shift type with the given name, this sets **st* to that shift type and returns true, otherwise it sets **st* to NULL and returns false. To visit the shift-type sets of an instance, call

```
int NrcInstanceShiftTypeSetCount(NRC_INSTANCE ins);
NRC_SHIFT_TYPE_SET NrcInstanceShiftTypeSet(NRC_INSTANCE ins, int i);
```

in the usual way. If a shift-type set has a non-NULL name, it may be retrieved by calling

```
bool NrcInstanceRetrieveShiftTypeSet(NRC_INSTANCE ins, char *name,
    NRC_SHIFT_TYPE_SET *sts);
```

in the usual way.

3.3.5. Shifts, shift-sets, and shift-set sets

The shifts of an instance are stored in the instance as a shift-set. To retrieve this shift-set call

```
NRC_SHIFT_SET NrcInstanceAllShifts(NRC_INSTANCE ins);
```

To visit the shifts one by one, call

```
int NrcInstanceShiftCount(NRC_INSTANCE ins);
NRC_SHIFT NrcInstanceShift(NRC_INSTANCE ins, int i);
```

as usual. (In many cases, however, a better way to visit each shift is to visit each day, and then visit each shift on that day.) Also, functions

```
NRC_SHIFT_SET NrcInstanceDailyStartingShiftSet(NRC_INSTANCE ins);
NRC_SHIFT_SET NrcInstanceWeeklyStartingShiftSet(NRC_INSTANCE ins);
```

return the set of shifts which are first in each day, and first in each week. These are useful values for the *starting_ss* parameter of *NrcConstraintMake* (Section 3.9.8). To visit all shift-sets, call

```
int NrcInstanceShiftSetCount(NRC_INSTANCE ins);
NRC_SHIFT_SET NrcInstanceShiftSet(NRC_INSTANCE ins, int i);
```

and to visit all shift-set sets, call

```
int NrcInstanceShiftSetSetCount(NRC_INSTANCE ins);
NRC_SHIFT_SET_SET NrcInstanceShiftSetSet(NRC_INSTANCE ins, int i);
```

in the usual way. There are also

```
NRC_SHIFT_SET_SET NrcInstanceDaysShiftSetSet(NRC_INSTANCE ins);
```

which returns a shift-set set containing one shift-set for each day of the cycle, holding the shifts of that day, and

```
NRC_SHIFT_SET_SET NrcInstanceShiftsShiftSetSet(NRC_INSTANCE ins);
```

which returns a shift-set set containing one shift-set for each shift, holding that shift.

3.3.6. Workers, worker-sets, and worker-set sets

Functions for creating and querying workers, worker-sets, and worker-set sets are given in Section 3.8. The workers of an instance are held in a worker-set in the instance called the *staffing*. It may be retrieved by calling

```
NRC_WORKER_SET NrcInstanceStaffing(NRC_INSTANCE ins);
```

For convenience, its elements may be visited directly by

```
int NrcInstanceStaffingWorkerCount(NRC_INSTANCE ins);
NRC_WORKER NrcInstanceStaffingWorker(NRC_INSTANCE ins, int i);
```

There is also

```
bool NrcInstanceStaffingRetrieveWorker(NRC_INSTANCE ins,
    char *name, NRC_WORKER *w);
```

which retrieves a worker with the given name from the staffing, setting **w* to that worker and returning *true* if successful, and setting **w* to *NULL* and returning *false* otherwise.

To visit all the worker-sets of an instance (including the staffing), call

```
int NrcInstanceWorkerSetCount(NRC_INSTANCE ins);
NRC_WORKER_SET NrcInstanceWorkerSet(NRC_INSTANCE ins, int i);
```

in the usual way. There is also

```
bool NrcInstanceRetrieveWorkerSet(NRC_INSTANCE ins, char *name,
    NRC_WORKER_SET *ws);
```

which retrieves a worker-set with the given name from the instance, setting **ws* to that worker-set and returning *true* if successful, and setting **ws* to *NULL* and returning *false* otherwise.

To visit all the worker-set sets of an instance, call

```
int NrcInstanceWorkerSetSetCount(NRC_INSTANCE ins);
NRC_WORKER_SET_SET NrcInstanceWorkerSetSet(NRC_INSTANCE ins, int i);
```

in the usual way.

3.3.7. Contracts and skills

Several nurse rostering models offer *contracts*, which are sets of constraints. A worker can be made subject to a contract, which means that the contract's constraints apply to that worker. At least one model allows a worker to be subject to more than one contract.

In NRC, a worker-set is used to model each contract. Its name is the name of the contract, perhaps with "Contract-" prepended, and its members are the workers subject to the contract. The contract's constraints are not stored in the worker-set. Instead, each constraint has a worker-set attribute saying which workers it applies to. When there are contracts, this would be the worker-set for the contract that the constraint lies within. When there are no contracts, it would be something else—the set of all workers returned by `NrcInstanceStaffing` above, perhaps, or `NrcWorkerSingletonWorkerSet(w)`, the worker-set containing just worker *w*.

Each NRC instance holds a worker-set set called the *contracts*, intended to hold the set of all contracts, although what it actually holds is up to the user. This worker-set set is not consulted when generating an instance; it is there only for the convenience of the user. (Exception: for documentation, a KHE resource group is generated for each contract, even if it is not used.)

To add a contract to the contracts, call

```
void NrcInstanceContractsAddContract(NRC_INSTANCE ins,
    NRC_WORKER_SET contract_ws);
```

To retrieve the contracts as a worker-set set, call

```
NRC_WORKER_SET_SET NrcInstanceContracts(NRC_INSTANCE ins);
```

To visit the contracts one by one, call

```
int NrcInstanceContractsContractCount(NRC_INSTANCE ins);
NRC_WORKER_SET NrcInstanceContractsContract(NRC_INSTANCE ins, int i);
```

To retrieve a contract by name, call

```
bool NrcInstanceContractsRetrieveContract(NRC_INSTANCE ins,
    char *name, NRC_WORKER_SET *contract_ws);
```

If the contracts contain a contract with the given name, this sets `*contract_ws` to a contract with that name and returns `true`, otherwise it sets `*contract_ws` to `NULL` and returns `false`.

It is acceptable to define the contract at one time and add workers to it later. Indeed, this is what usually happens, given that contracts are defined at one point in the source file and workers declare their adherence to a contract at another.

Most nurse rostering models offer *skills*. A skill is some capability that a worker has, such as being a senior nurse, or a CPR expert. A worker may have any number of skills. A demand for a worker may require that a worker with a particular skill be assigned. If a worker without that skill is assigned, there is a penalty, which may vary depending on which worker is assigned.

Again, in NRC a worker-set is used to model each skill. Its name is the name of the skill, and its elements are the workers who have that skill. Each demand has an optional worker-set attribute specifying the skill that workers satisfying that demand should have.

Each NRC instance holds a worker-set set called the *skills*, intended to hold the set of all skills, although what it actually holds is up to the user. This worker-set set is not consulted when generating an instance; it is there only for the convenience of the user. (Exception: for documentation, a KHE resource group is generated for each skill, even if it is not used.)

Operations entirely analogous to those for the contracts are offered for the skills:

```
void NrcInstanceSkillsAddSkill(NRC_INSTANCE ins,
    NRC_WORKER_SET skill_ws);
NRC_WORKER_SET_SET NrcInstanceSkills(NRC_INSTANCE ins);
int NrcInstanceSkillsSkillCount(NRC_INSTANCE ins);
NRC_WORKER_SET NrcInstanceSkillsSkill(NRC_INSTANCE ins, int i);
bool NrcInstanceSkillsRetrieveSkill(NRC_INSTANCE ins,
    char *name, NRC_WORKER_SET *skill_ws);
```

The contracts and skills may well be the only worker-sets the user needs. There is nothing to prevent a worker from lying within two or more contracts, or two or more skills. Indeed, this is quite normal, at least for skills.

3.3.8. Demands, demand-sets, patterns, and constraints

Functions for creating and querying demands, demand-sets, patterns, pattern sets, and constraints are given in Section 3.9. All these objects are stored in the instance. Demands may be visited by

```
int NrcInstanceDemandCount(NRC_INSTANCE ins);
NRC_DEMAND NrcInstanceDemand(NRC_INSTANCE ins, int i);
```

and demand-sets may be visited by

```
int NrcInstanceDemandSetCount(NRC_INSTANCE ins);
NRC_DEMAND_SET NrcInstanceDemandSet(NRC_INSTANCE ins, int i);
```

in the usual way. Patterns may be visited by

```
int NrcInstancePatternCount(NRC_INSTANCE ins);
NRC_PATTERN NrcInstancePattern(NRC_INSTANCE ins, int i);
```

in the usual way, and patterns with a non-NULL name may be retrieved by calling

```
bool NrcInstanceRetrievePattern(NRC_INSTANCE ins, char *name,
    NRC_PATTERN *p);
```

The stored patterns are not used privately by NRC; in particular, they do not become unwanted unless they are added to worker constraints. Pattern sets are may be visited by

```
int NrcInstancePatternSetCount(NRC_INSTANCE ins);
NRC_PATTERN_SET NrcInstancePatternSet(NRC_INSTANCE ins, int i);
```

Pattern sets have no names so there is no retrieve operation.

Demand constraints and worker constraints are stored in the instance, and may be

visited by

```
int NrcInstanceDemandConstraintCount(NRC_INSTANCE ins);
NRC_DEMAND_CONSTRAINT NrcInstanceDemandConstraint(NRC_INSTANCE ins,
    int i);
```

and

```
int NrcInstanceConstraintCount(NRC_INSTANCE ins);
NRC_CONSTRAINT NrcInstanceConstraint(NRC_INSTANCE ins, int i);
```

in the usual way.

3.4. Days

In informal discourse, a day could be a specific day, such as 23 July 2016, or it could be a day of the week, such as Friday. In NRC and this documentation, the term *day* always refers to a specific day, represented by an object of type `NRC_DAY`.

3.4.1. The cycle and the days of the week

There is no NRC function for creating one day. Instead, there is a function for creating the *cycle*, the set of all days of an instance:

```
void NrcCycleMake(NRC_INSTANCE ins, int day_count, int first_day_index);
```

`NrcCycleMake` adds to `ins` a cycle of `day_count` days. Parameter `first_day_index` says which day of the week the first day is on: 0 means that the first day is a Sunday, 1 means that the first day is a Monday, and so on.

Although the days created by `NrcCycleMake` are specific days, they are not associated with calendar dates. To get days with calendar dates, call `NrcCalendarCycleMake` instead:

```
bool NrcCalendarCycleMake(NRC_INSTANCE ins,
    char *start_ymd, char *end_ymd, char **err_str);
```

`NrcCalendarCycleMake` creates a cycle with first day `start_ymd` and last day `end_ymd`, where the two strings are given in YYYY-MM-DD format. (Actually, the format is just three non-negative integers separated by hyphens; but the dates actually stored are normalized to the format shown.) The Unix `mktime` function is used to find out which day of the week `start_ymd` is on, and other important facts such as the number of days in each month. The two days are arbitrary except that there must be at least one day in the cycle. Value `true` is returned if successful; otherwise `false` is returned and `err_str` is set to an error message explaining what went wrong. This will be some problem with `start_ymd` or `end_ymd`, such as being formatted wrongly or specifying a non-existent date.

3.4.2. Days

A *day* in NRC is an object of type `NRC_DAY` representing a specific day, such as Monday 21 November 2016, although the calendar date of the day need not be known.

There is no function for creating an individual day. Instead, functions `NrcCycleMake` and `NrcCalendarCycleMake` (Section 3.4.1) are called, to make all the days at once. The days created by these functions can be accessed using functions `NrcInstanceCycleDayCount` and `NrcInstanceCycleDay` (Section 3.3.3).

The basic attributes of a day may be found by calling

```
NRC_INSTANCE NrcDayInstance(NRC_DAY d);
char *NrcDayYMD(NRC_DAY d);
char *NrcDayShortName(NRC_DAY d);
char *NrcDayLongName(NRC_DAY d);
```

`NrcDayInstance` returns the enclosing instance. `NrcDayYMD` returns the date of day `d` in YYYY-MM-DD format if the day was created by `NrcCalendarCycleMake`, or "-" otherwise. `NrcDayShortName` and `NrcDayLongName` return the name of the day in either short and long form, consisting of a week number followed by a short or long day name as defined by `NrcInstanceSetDayNames` (Section 3.3.2). For example, `1Mon` is the short name of the day which represents the Monday of the first week of the cycle.

Several functions return integer indexes defining the position of the day in the cycle:

```
int NrcDayIndexInCycle(NRC_DAY d);
int NrcDayWeekInCycle(NRC_DAY d);
int NrcDayIndexInWeek(NRC_DAY d);
```

`NrcDayIndexInCycle` returns the index of `d` in the cycle: 0 for the first day, 1 for the second, and so on. `NrcDayWeekInCycle` returns the number of the week that `d` lies in. The first 7 days of the cycle have week number 1, the second 7 days have week number 2, and so on, irrespective of the day of the week the cycle begins on. `NrcDayIndexInWeek` returns the index of `d`'s day of the week: 0 for Sunday, 1 for Monday, and so on (which is how the Unix `mktime` function does it). NRC does not have an `NRC_WEEK` data type.

Functions

```
NRC_DAY NrcDayPrev(NRC_DAY d);
NRC_DAY NrcDayNext(NRC_DAY d);
```

return the day preceding `d` in the cycle, or `NULL` when `d` is the first day, and the day following `d` in the cycle, or `NULL` when `d` is the last day.

A surprisingly useful function is

```
NRC_DAY_SET NrcDayDayOfWeek(NRC_DAY d);
```

which returns `d`'s day of the week. NRC does not have a data type for day of the week. Instead, a day of the week is represented by an `NRC_DAY_SET` object holding a set of days—all the days that fall on the same day of the week. The day set objects returned by `NrcDayDayOfWeek` are created by `NrcCycleMake` and `NrcCalendarCycleMake` while they are creating the days; the user does not need to create them. Another function that returns a day-set is

```
NRC_DAY_SET NrcDaySingletonDaySet(NRC_DAY d);
```

The result is a day-set containing just *d*.

Function

```
NRC_SHIFT_SET NrcDayShiftSet(NRC_DAY d);
```

returns a shift-set containing the shifts of *d*. There is one of these for each shift type, in the order that the shift types were added to the instance. For convenience,

```
int NrcDayShiftCount(NRC_DAY d);
NRC_SHIFT NrcDayShift(NRC_DAY d, int i);
```

can be used to visit this shift-set's shifts directly. Function

```
NRC_SHIFT NrcDayShiftFromShiftType(NRC_DAY d, NRC_SHIFT_TYPE st);
```

returns the shift with day *d* and type *st*, i.e. `NrcDayShift(d, NrcShiftTypeIndex(st))`, and

```
NRC_SHIFT_SET NrcDayShiftSetFromShiftTypeSet(NRC_DAY d,
NRC_SHIFT_TYPE_SET sts);
```

does this for each element of *sts*, producing a shift-set. There is also

```
NRC_SHIFT_SET_SET NrcDayShiftSetSet(NRC_DAY d);
```

which returns a shift-set set containing one shift-set for each shift on day *d*, namely the singleton shift-set holding that shift.

To produce a debug print of day *d*, call

```
void NrcDayDebug(NRC_DAY d, int indent, FILE *fp);
```

This works as explained in Section 3.2.

3.4.3. Day-sets

A *day-set* is a set (more precisely, a sequence) of days. Although any days can make up a day-set, the most likely combinations are adjacent days (for example, the days of a weekend) and days that share the same day of the week (for example, the set of all Mondays in the cycle).

`NrcCycleMake` and `NrcCalendarCycleMake` make day-sets: one holding the cycle as a whole, and one for each of the seven days of the week (the day-set of all Mondays, the day-set of all Tuesdays, and so on). Day-sets can also be created by the user, by calling

```
NRC_DAY_SET NrcDaySetMake(NRC_INSTANCE ins, char *short_name,
char *long_name);
void NrcDaySetAddDay(NRC_DAY_SET ds, NRC_DAY d);
```

in the usual way. Both names must be non-NULL. Functions

```
NRC_INSTANCE NrcDaySetInstance(NRC_DAY_SET ds);
char *NrcDaySetShortName(NRC_DAY_SET ds);
char *NrcDaySetLongName(NRC_DAY_SET ds);
```

return the attributes of day-set *ds*, functions

```
int NrcDaySetDayCount(NRC_DAY_SET ds);
NRC_DAY NrcDaySetDay(NRC_DAY_SET ds, int i);
```

visit the days in the order they were inserted,

```
bool NrcDaySetContainsDay(NRC_DAY_SET ds, NRC_DAY d);
```

returns true when *ds* contains *d*, and

```
bool NrcDaySetRetrieveDay(NRC_DAY_SET ds, char *ymd, NRC_DAY *d);
```

retrieves a day from *ds* by its *ymd* value. The date string must contain three non-negative integers separated by hyphens; a copy, normalized to a four-digit year and two-digit month and day, is used when retrieving.

Function

```
bool NrcDaySetsOverlap(NRC_DAY_SET ds1, NRC_DAY_SET ds2);
```

returns true when *ds1* and *ds2* have a non-empty intersection. And

```
NRC_DAY_SET NrcDaySetDifference(NRC_DAY_SET ds1, NRC_DAY_SET ds2);
```

returns a new day-set containing the days of *ds1* that are not in *ds2*.

Function

```
NRC_SHIFT_SET NrcDaySetShiftSet(NRC_DAY_SET ds);
```

returns a shift-set containing all the shifts on all the days of *ds*, while

```
NRC_SHIFT_SET NrcDaySetStartingShiftSet(NRC_DAY_SET ds);
```

returns a shift-set containing the first shift on each day of *ds*. This helps when constructing suitable values for the *starting_ss* parameter of *NrcConstraintMake* (Section 3.9.8). If any of the shift-sets of the days of *ds* is empty, *NrcDaySetStartingShiftSet* aborts. Also,

```
NRC_SHIFT_SET_SET NrcDaySetShiftSetSet(NRC_DAY_SET ds);
```

returns a shift-set set containing one shift-set for each day of *ds*, holding that day's shifts. And

```
NRC_SHIFT_SET NrcDaySetShiftSetFromShiftTypeSet(NRC_DAY_SET ds,
NRC_SHIFT_TYPE_SET sts);
```

returns a shift-set containing all shifts whose day is in *ds* and whose shift type is in *sts*.

Function

```
void NrcDaySetDebug(NRC_DAY_SET ds, int indent, FILE *fp);
```

produces a debug print of *ds* onto *fp*, as explained in Section 3.2.

3.4.4. Day-set sets

A *day-set set* is a set (more precisely, a sequence) of day-sets. For example, 1Sat is a day, {1Sat, 1Sun} is a day-set representing one weekend, and

```
{ {1Sat, 1Sun}, {2Sat, 2Sun}, {3Sat, 3Sun}, {4Sat, 4Sun} }
```

is a day-set set representing (possibly) the set of all weekends in the cycle.

To create a day-set set and add day-sets to it, the functions are

```
NRC_DAY_SET_SET NrcDaySetSetMake(NRC_INSTANCE ins, char *short_name,
    char *long_name);
void NrcDaySetSetAddDaySet(NRC_DAY_SET_SET dss, NRC_DAY_SET ds);
```

Functions

```
NRC_INSTANCE NrcDaySetSetInstance(NRC_DAY_SET_SET dss);
char *NrcDaySetSetShortName(NRC_DAY_SET_SET dss);
char *NrcDaySetSetLongName(NRC_DAY_SET_SET dss);
```

return the attributes of a day-set set, and

```
int NrcDaySetSetDaySetCount(NRC_DAY_SET_SET dss);
NRC_DAY_SET NrcDaySetSetDaySet(NRC_DAY_SET_SET dss, int i);
bool NrcDaySetSetRetrieveDaySet(NRC_DAY_SET_SET dss,
    char *long_name, NRC_DAY_SET *ds);
```

are used to visit the day-sets of a day-set set in the order they were inserted, and to retrieve a day-set from a day-set set by long name. And

```
void NrcDaySetSetDebug(NRC_DAY_SET_SET dss, int indent, FILE *fp);
```

produces a debug print of dss onto fp, as explained in Section 3.2.

3.5. Time intervals

A *time interval* is an interval of time, consisting of a start time and an end time, measured in seconds since midnight. These are not absolute intervals like ‘10am to 11am on 7 April 2007’, but rather generic ones, like ‘10am to 11am’.

As is common in nurse rostering, an end time may be smaller than a start time, meaning that the interval spans midnight. Strictly speaking, then, what is representable is a time interval that starts at any time of day and ends less than 24 hours later, on the same day or the following day.

Before considering operations on time intervals proper, here are two more basic functions. The first converts a string in HH:MM:SS or HH:MM format into an integer number of seconds:

```
bool NrcHMSToSecs(char *hms, int *res);
```

It returns true and sets *res to the number of seconds if successful, and returns false and sets *res to -1 if not successful (because hms has a format problem). The second function,

```
char *NrcSecsToHMS(int secs, HA_ARENA a);
```

converts an integer number of seconds to a string in HH:MM:SS format stored in arena a.

To create a time interval, call

```
NRC_TIME_INTERVAL NrcTimeIntervalMake(int start_secs, int end_secs,
    NRC_INSTANCE ins);
```

The new object will be stored in the arena of `ins` and deleted when the instance is deleted. There are $24 * 60 * 60$ seconds in a day, so `start_secs` and `end_secs` must satisfy

```
0 <= start_secs < 24 * 60 * 60
0 < end_secs <= 24 * 60 * 60
```

Disallowing `start_secs == 24 * 60 * 60` and `end_secs == 0` ensures that there is only one way to represent any non-empty interval, including intervals that start or end at midnight.

Function

```
bool NrcTimeIntervalMakeFromHMS(char *start_hms, char *end_hms,
    NRC_TIME_INTERVAL *res, NRC_INSTANCE ins);
```

converts `start_hms` and `end_hms` using `NrcHMSToSecs` above, and makes a time interval from them, returning `true` and setting `*res` to it if successful, and returning `false` and setting `*res` to `NULL` if unsuccessful, because `start_hms` or `end_hms` has a format problem or is out of range. As occurs in instances, `end_hms` may be `00:00:00`, which is taken to mean `24:00:00`.

The two basic queries are

```
int NrcTimeIntervalStartSecs(NRC_TIME_INTERVAL ti);
int NrcTimeIntervalEndSecs(NRC_TIME_INTERVAL ti);
```

There are also set operations on time intervals:

```
bool NrcTimeIntervalEqual(NRC_TIME_INTERVAL ti1, NRC_TIME_INTERVAL ti2);
bool NrcTimeIntervalDisjoint(NRC_TIME_INTERVAL ti1, NRC_TIME_INTERVAL ti2);
bool NrcTimeIntervalSubset(NRC_TIME_INTERVAL ti1, NRC_TIME_INTERVAL ti2);
```

These return `true` when `ti1` and `ti2` are equal, or disjoint, or when `ti1` is a subset of `ti2`. These operations consider intervals to be *open*, that is, to not include their endpoints. So when one interval's end time equals another's start time, the two intervals are disjoint. They also understand what it means when `end_secs < start_secs`, and act accordingly. Function

```
NRC_SHIFT_SET NrcTimeIntervalShiftSet(NRC_TIME_INTERVAL ti, NRC_DAY d);
```

returns a shift-set containing those shifts which have time intervals which intersect with (are not disjoint with) time interval `ti` on day `d`. The shifts of the result do not necessarily all come from day `d`; some may come from the previous day if they span midnight and there is a previous day, while others may come from the next day if `ti` spans midnight and there is a next day. Finally,

```
char *NrcTimeIntervalShow(NRC_TIME_INTERVAL ti, HA_ARENA a);
```

returns a string, stored in arena `a`, representing time interval `ti`.

3.6. Shift types

In informal discourse, a shift could be a specific shift, such as the night shift on 23 July 2016, or it could be a generic shift, such as the night shift. In NRC, a generic shift is called a *shift type*, and a specific shift is called a *shift*. There is one shift of each shift type on each day.

3.6.1. Shift types

A *shift type* is a generic shift, such as ‘the day shift’ or ‘the night shift’. To make one, call

```
NRC_SHIFT_TYPE NrcShiftTypeMake(NRC_INSTANCE ins, char *name,
    int workload);
```

This creates a new shift type object with the given name and workload (explained below), adds it to *ins*, and returns it. To retrieve its attributes, call

```
NRC_INSTANCE NrcShiftTypeInstance(NRC_SHIFT_TYPE st);
char *NrcShiftTypeName(NRC_SHIFT_TYPE st);
int NrcShiftTypeWorkload(NRC_SHIFT_TYPE st);
int NrcShiftTypeIndex(NRC_SHIFT_TYPE st);
```

NrcShiftTypeIndex returns *st*’s index in the instance (0 for the first shift type added, 1 for the second, and so on). There is also

```
NRC_SHIFT_TYPE_SET NrcShiftTypeSingletonShiftTypeSet(NRC_SHIFT_TYPE st);
```

which returns a shift-type set containing just *st*.

The workload is a value in arbitrary units (for example, in minutes), describing how much work a shift of this type is. It is only needed when there are worker constraints that limit total workload. When it is not needed, *NRC_NO_WORKLOAD* (a synonym for 1) should be passed.

Two functions give access to the shifts of type *st*:

```
NRC_SHIFT_SET NrcShiftTypeShiftSet(NRC_SHIFT_TYPE st);
NRC_SHIFT_SET_SET NrcShiftTypeShiftSetSet(NRC_SHIFT_TYPE st);
```

NrcShiftTypeShiftSet returns a shift-set containing all shifts which have *st* for their shift type, in increasing day order. *NrcShiftTypeShiftSetSet* is similar, except that each shift lies in its own singleton shift set.

There is no *NrcShiftTypeDebug* function, because a shift type is essentially just its name. Use *NrcShiftTypeName* instead.

There is one shift for each shift type on each day. It does not matter to NRC whether days or shift types are added first. When a day is added, one shift of each existing type is added to the day. When a shift type is added, one shift of the new type is added for each existing day.

A shift type may optionally contain a time interval. It is not used by NRC, but it may be useful to the user. The operations for setting and retrieving it are

```
void NrcShiftTypeAddTimeInterval(NRC_SHIFT_TYPE st, NRC_TIME_INTERVAL ti);
NRC_TIME_INTERVAL NrcShiftTypeTimeInterval(NRC_SHIFT_TYPE st);
```

`NrcShiftTypeTimeInterval` returns `NULL` when `st`'s time interval has not been set.

The author hesitated over whether to include shift types, since a shift-set with the name of the shift type does most of what a shift type does. However, to construct that shift-set one needs some way to identify what is common to its shifts—a name, presumably; but then that is the name of a shift type, not of a shift. More importantly, with shift types available, NRC can make the individual shifts itself, and guarantee a uniform structure of one shift of each type on each day. This uniformity matters, for example, when implementing patterns. If some of these shifts do not need to be covered on some days (for example, if the early shift does not need to be staffed on Sundays), one can just add no demands to those shifts.

3.6.2. Shift-type sets

A *shift-type set* is a set of shift types. It is created in the usual way:

```
NRC_SHIFT_TYPE_SET NrcShiftTypeSetMake(NRC_INSTANCE ins, char *name);
void NrcShiftTypeSetAddShiftType(NRC_SHIFT_TYPE_SET sts, NRC_SHIFT_TYPE st);
```

The name is optional (may be `NULL`). Its attributes are returned by

```
NRC_INSTANCE NrcShiftTypeSetInstance(NRC_SHIFT_TYPE_SET sts);
char *NrcShiftTypeSetName(NRC_SHIFT_TYPE_SET sts);
```

and its shift types are visited by

```
int NrcShiftTypeSetShiftTypeCount(NRC_SHIFT_TYPE_SET sts);
NRC_SHIFT_TYPE NrcShiftTypeSetShiftType(NRC_SHIFT_TYPE_SET sts, int i);
```

There are also

```
bool NrcShiftTypeSetContainsShiftType(NRC_SHIFT_TYPE_SET sts,
NRC_SHIFT_TYPE st);
```

which returns `true` when `sts` contains `st`,

```
bool NrcShiftTypeSetEqual(NRC_SHIFT_TYPE_SET sts1,
NRC_SHIFT_TYPE_SET sts2);
```

which returns `true` when `sts1` and `sts2` contain the same shift types, and

```
bool NrcShiftTypeSetDisjoint(NRC_SHIFT_TYPE_SET sts1,
NRC_SHIFT_TYPE_SET sts2);
```

which returns `true` when they are disjoint. Finally,

```
NRC_SHIFT_TYPE_SET NrcShiftTypeSetMerge(NRC_SHIFT_TYPE_SET sts1,
NRC_SHIFT_TYPE_SET sts2);
```

returns a new shift-type set containing the set union of `sts1` and `sts2`. Shift-type sets are mainly used when constructing patterns (Section 3.9.6).

3.7. Shifts

3.7.1. Shifts

There are no functions for creating individual shifts. Instead, NRC automatically creates one shift, of type `NRC_SHIFT`, for each shift type on each day. These shifts can be accessed as elements of the shift-sets returned by `NrcShiftTypeShiftSet` and `NrcDayShiftSet`, or using `NrcInstanceShiftCount` and `NrcInstanceShift`.

To retrieve the basic attributes of a shift, call

```
NRC_INSTANCE NrcShiftInstance(NRC_SHIFT s);
NRC_DAY NrcShiftDay(NRC_SHIFT s);
NRC_SHIFT_TYPE NrcShiftType(NRC_SHIFT s);
```

There is also

```
NRC_SHIFT_SET NrcShiftSingletonShiftSet(NRC_SHIFT s);
```

which returns a shift-set containing just `s`.

A shift has an optional workload, measured in arbitrary units, for example minutes:

```
int NrcShiftWorkload(NRC_SHIFT s);
```

The workload of a shift is the workload of its shift type, and this cannot be changed.

To add a demand (Section 3.9.3) to a shift, specifying that a worker, optionally with a certain skill, needs to be assigned to that shift, call

```
void NrcShiftAddDemand(NRC_SHIFT s, NRC_DEMAND d);
```

Any number of demands may be added in this way; their total number is the total number of workers demanded by the shift. There are also the convenience functions

```
void NrcShiftAddDemandMulti(NRC_SHIFT s, NRC_DEMAND d, int multiplicity);
void NrcShiftAddDemandSet(NRC_SHIFT s, NRC_DEMAND_SET ds);
```

`NrcShiftAddDemandMulti` adds `d` to `s` `multiplicity` times, while `NrcShiftAddDemandSet` adds the demands of `ds` individually to `s`. The fact that these demands arrived in a group is not remembered. To visit the demands of shift `s`, call

```
int NrcShiftDemandCount(NRC_SHIFT s);
NRC_DEMAND NrcShiftDemand(NRC_SHIFT s, int i);
```

as usual. Demands are immutable objects and may be shared by several shifts, and added to the same shift several times, when several workers with the same characteristics are wanted. In fact, behind the scenes NRC forces you to share demands: the demand object returned by `NrcDemandMake` is only new when there is no existing demand with the same attributes. This helps to reduce the size of the generated XESTT file, as it turns out.

Workers can be preassigned to shifts by calling

```
void NrcShiftAddPreassignment(NRC_SHIFT s, NRC_WORKER w);
```

To visit these preassignments, call

```
int NrcShiftPreassignmentCount(NRC_SHIFT s);
NRC_WORKER NrcShiftPreassignment(NRC_SHIFT s, int i);
```

as usual. This works in simple cases, but be warned that the implementation is rough and ready. At present there is no way to indicate that the preassigned worker should fill a particular role or satisfy the demand for a particular skill. And if the preassignments cannot all be included in the XESTT event which is the result of converting the shift, NRC aborts with an error message.

Function

```
void NrcShiftDebug(NRC_SHIFT s, int indent, FILE *fp);
```

produces a debug print of `s` onto `fp`, as explained in Section 3.2.

3.7.2. Shift-sets

A shift-set is a set of shifts. To make a shift-set, use

```
NRC_SHIFT_SET NrcShiftSetMake(NRC_INSTANCE ins, char *name);
void NrcShiftSetAddShift(NRC_SHIFT_SET ss, NRC_SHIFT s);
```

as usual; or to add the shifts of another shift-set `ss2` to shift-set `ss` all at once, call

```
void NrcShiftSetAddShiftSet(NRC_SHIFT_SET ss, NRC_SHIFT_SET ss2);
```

To retrieve the attributes, call

```
NRC_INSTANCE NrcShiftSetInstance(NRC_SHIFT_SET ss);
char *NrcShiftSetName(NRC_SHIFT_SET ss);
int NrcShiftSetShiftCount(NRC_SHIFT_SET ss);
NRC_SHIFT NrcShiftSetShift(NRC_SHIFT_SET ss, int i);
```

There is also

```
bool NrcShiftSetContainsShift(NRC_SHIFT_SET ss, NRC_SHIFT s);
```

which returns true when `ss` contains `s`.

The shifts of a shift-set may be arbitrary, but often they will be all the shifts of a particular day, or all the shifts with a particular shift type. These shift-sets are constructed automatically by NRC, and are obtained by calling `NrcDayShiftSet` and `NrcShiftTypeShiftSet`.

Function

```
void NrcShiftSetDebug(NRC_SHIFT_SET ss, int indent, FILE *fp);
```

produces a debug print of `ss` onto `fp` with the given indent, as described in Section 3.2.

3.7.3. Shift-set sets

A shift-set set is a set of shift-sets. To make a shift-set set, call

```
NRC_SHIFT_SET_SET NrcShiftSetSetMake(char *name);
void NrcShiftSetSetAddShiftSet(NRC_SHIFT_SET_SET sss, NRC_SHIFT_SET ss);
```

To retrieve the name and the shift-sets, call

```
char *NrcShiftSetSetName(NRC_SHIFT_SET_SET sss);
int NrcShiftSetSetShiftSetCount(NRC_SHIFT_SET_SET sss);
NRC_SHIFT_SET NrcShiftSetSetShiftSet(NRC_SHIFT_SET_SET sss, int i);
```

in the usual way.

Function

```
NRC_SHIFT_SET NrcShiftSetSetStartingShiftSet(NRC_SHIFT_SET_SET sss);
```

returns a shift-set containing the first shift from each shift-set of *sss*. This helps when constructing values for the *starting_ss* parameter of *NrcConstraintMake* (Section 3.9.8). If any of the shift-sets of *sss* is empty, *NrcShiftSetSetStartingShiftSet* aborts. Function

```
void NrcShiftSetSetDebug(NRC_SHIFT_SET_SET sss, int indent, FILE *fp);
```

produces a debug print of *sss* onto *fp*, as explained in Section 3.2.

3.8. Workers

A *worker* is one person capable of filling shifts. The term ‘worker’ has been preferred to ‘nurse’ because it is more general, and to ‘employee’ because it is shorter.

3.8.1. Workers

To create a worker, call

```
NRC_WORKER NrcWorkerMake(NRC_INSTANCE ins, char *name);
```

The new object is added to *ins* and returned. The basic attributes may be retrieved by

```
NRC_INSTANCE NrcWorkerInstance(NRC_WORKER w);
char *NrcWorkerName(NRC_WORKER w);
```

as usual. There is also

```
int NrcWorkerIndex(NRC_WORKER w);
```

which returns the index of *w* in the instance (the number of previously created workers), and

```
NRC_WORKER_SET NrcWorkerSingletonWorkerSet(NRC_WORKER w);
```

which returns a worker-set (Section 3.8.2) containing just *w*.

In some models, when a worker without the appropriate skill is assigned to a shift, the penalty (Section 3.9.1) varies with the worker. In those cases, call function

```
void NrcWorkerAddSkillPenalty(NRC_WORKER w, NRC_PENALTY p);
```

to add this penalty to worker *w*. This may be done at most once per worker. Function

```
NRC_PENALTY NrcWorkerSkillPenalty(NRC_WORKER w);
```

returns this penalty, or NULL if `NrcWorkerAddSkillPenalty` has not been called for *w*.

To say that a worker wants a particular shift, shift-set, or day off, call

```
extern void NrcWorkerAddShiftOff(NRC_WORKER w, NRC_SHIFT s, NRC_PENALTY p);
extern void NrcWorkerAddShiftSetOff(NRC_WORKER w, NRC_SHIFT_SET ss,
    NRC_PENALTY p);
extern void NrcWorkerAddDayOff(NRC_WORKER w, NRC_DAY d, NRC_PENALTY p);
```

Requesting a shift-set or day off means requesting that no shift of that shift-set or day be assigned. The *p* parameters give the penalty for failing to satisfy the request. These penalties may differ from one request to another, even for the same worker. Similarly, to say that a worker wants a particular shift, shift-set, or day on, call

```
void NrcWorkerAddShiftOn(NRC_WORKER w, NRC_SHIFT s, NRC_PENALTY p);
void NrcWorkerAddShiftSetOn(NRC_WORKER w, NRC_SHIFT_SET ss, NRC_PENALTY p);
void NrcWorkerAddDayOn(NRC_WORKER w, NRC_DAY d, NRC_PENALTY p);
```

Requesting a shift-set or day on means requesting that some shift of that shift-set or day be assigned, without caring which. By calling `NrcShiftAddPreassignment` (Section 3.7.1), a resource may also be preassigned to a shift—essentially an unbreakable shift-on request. Also,

```
void NrcWorkerAddStartDay(NRC_WORKER w, NRC_DAY d, NRC_PENALTY p);
void NrcWorkerAddEndDay(NRC_WORKER w, NRC_DAY d, NRC_PENALTY p);
```

say that *w* is only available starting at day *d*, or ending at day *d*. The given penalties apply to every assignment before the start day or after the end day.

Some models include *history*: information about what a worker did before the current instance began. NRC offers these two functions for handling a worker's history:

```
void NrcWorkerAddHistory(NRC_WORKER w, char *name, int value);
bool NrcWorkerRetrieveHistory(NRC_WORKER w, char *name, int *value);
```

`NrcWorkerAddHistory` associates *value* with *name* within *w*, and `NrcWorkerRetrieveHistory` sets **value* to the value associated with *name* within *w*, or returns false if there is no value associated with *name*. For example,

```
NrcWorkerAddHistory(w, "WeekendsWorked", 10);
```

says that *w* has worked 10 weekends before the current instance begins.

NRC does not understand what the names mean or use history itself; it simply stores it so that the user can retrieve it later when generating constraints (Section 3.9.10).

Although only integer values may be stored, it is easy to get around this. For example, the leading model which includes history mainly uses integers, but it does include one shift type. This may be stored as the index of the shift type in the instance.

Function

```
void NrcWorkerDebug(NRC_WORKER w, int indent, FILE *fp);
```

produces a debug print of `w` onto `fp`, as explained in Section 3.2.

3.8.2. Worker-sets

A worker-set is a set of workers. To create a new, empty worker-set, call

```
NRC_WORKER_SET NrcWorkerSetMake(NRC_INSTANCE ins, char *name);
```

where `name` is a unique name for the worker-set (it may not be `NULL`). To retrieve these two attributes, call

```
NRC_INSTANCE NrcWorkerSetInstance(NRC_WORKER_SET ws);
char *NrcWorkerSetName(NRC_WORKER_SET ws);
```

To add a worker to a worker-set, call

```
void NrcWorkerSetAddWorker(NRC_WORKER_SET ws, NRC_WORKER w);
```

A worker-set may contain any number of workers, and a worker may lie in any number of worker-sets. There is also

```
void NrcWorkerSetAddWorkerSet(NRC_WORKER_SET ws1, NRC_WORKER_SET ws2);
```

which adds the workers of `ws2` to `ws1`.

To visit the workers of a worker-set, call

```
int NrcWorkerSetWorkerCount(NRC_WORKER_SET ws);
NRC_WORKER NrcWorkerSetWorker(NRC_WORKER_SET ws, int i);
```

with the first worker having index 0 as usual. However, the workers are not stored in the order they are added; they are stored in order of increasing `NrcWorkerIndex`. This is done to facilitate comparisons between worker sets to see whether they have the same workers. There is also

```
bool NrcWorkerSetContainsWorker(NRC_WORKER_SET ws, NRC_WORKER w);
```

This returns `true` when `ws` contains `w`. And there is also

```
bool NrcWorkerSetRetrieveWorker(NRC_WORKER_SET ws, char *name,
    NRC_WORKER *w);
```

If `ws` contains a worker with the given name, it sets `*w` to one such worker and returns `true`. Otherwise it sets `*w` to `NULL` and returns `false`.

There is nothing to prevent the same worker from being added twice. Function

```
bool NrcWorkerSetHasNoDuplicates(NRC_WORKER_SET ws);
```

returns `true` when this has not occurred in `ws`.

Functions

```
bool NrcWorkerSetEqual(NRC_WORKER_SET ws1, NRC_WORKER_SET ws2);
bool NrcWorkerSetDisjoint(NRC_WORKER_SET ws1, NRC_WORKER_SET ws2);
bool NrcWorkerSetSubset(NRC_WORKER_SET ws1, NRC_WORKER_SET ws2);
```

return true when *ws1*'s set of workers is equal to *ws2*'s (the name, and the order in which the workers were added, may differ), when *ws1* and *ws2* have no workers in common, and when every worker in *ws1* is also in *ws2*. Function

```
void NrcWorkerSetDebug(NRC_WORKER_SET ws, int indent, FILE *fp);
```

produces a debug print of *ws* onto *fp*, as explained in Section 3.2.

NRC will abort if an attempt is made to create two worker-sets with the same name. Most worker-sets represent skills and contracts (Section 3.3.6), and name clashes are easily avoided there. The result of `NrcWorkerSingletonWorkerSet(w)` is created the first time it is called for; its name is *w*'s name. NRC also creates its own worker-sets, one with name "RG:All" holding all workers, and others to do with penalizing the assignment of workers to shifts they are not qualified for. These last have obscure names that do not clash with each other and are unlikely to clash with others. In short, you can forget about worker-set name clashes until you get one.

Worker-sets have a useful property: they can be used (passed to worker constraints, for example) before workers are added to them. This applies to all worker-sets: the staffing worker-set (holding all workers), contract and skill worker-sets, whatever. As long as the workers are added eventually, before `NrcArchiveWrite`, everything works; but see Section 4.4 for a caveat.

3.8.3. Worker-set sets

A *worker-set set* is a set of worker-sets. To define one, call functions

```
NRC_WORKER_SET_SET NrcWorkerSetSetMake(NRC_INSTANCE ins);
NRC_INSTANCE NrcWorkerSetSetInstance(NRC_WORKER_SET_SET wss);
void NrcWorkerSetSetAddWorkerSet(NRC_WORKER_SET_SET wss, NRC_WORKER_SET ws);
```

in the usual way. To visit the elements of a worker-set set, call functions

```
int NrcWorkerSetSetWorkerSetCount(NRC_WORKER_SET_SET wss);
NRC_WORKER_SET NrcWorkerSetSetWorkerSet(NRC_WORKER_SET_SET wss, int i);
```

The first element has index 0 as usual. There is also

```
bool NrcWorkerSetSetRetrieveWorkerSet(NRC_WORKER_SET_SET wss,
char *name, NRC_WORKER_SET *ws);
```

If *wss* contains a worker-set with the given name, this function sets **ws* to that worker-set and returns true. Otherwise it sets **ws* to NULL and returns false. Function

```
void NrcWorkerSetSetDebug(NRC_WORKER_SET_SET wss, int indent, FILE *fp);
```

produces a debug print of *wss* onto *fp*, as explained in Section 3.2.

3.8.4. Worker-set trees

A *worker-set tree* is a tree whose nodes are sets of worker-sets from a common instance *ins*, subject to the following conditions:

- The worker-sets that share any given node contain the same workers;
- The root of the tree contains `NrcInstanceStaffing(ins)`, the set of all workers;
- The worker-sets of a node are subsets of the worker-sets of its parent, if any;
- The worker-sets of sibling nodes are disjoint.

This structure turns out to be useful when disentangling cover requirements for overlapping skills, although the preferred approach at present is to leave them entangled and use limit resources constraints. To create a worker-set tree, call

```
NRC_WORKER_SET_TREE NrcWorkerSetTreeMake(NRC_INSTANCE ins);
```

The result has one node, containing one worker-set: `NrcInstanceStaffing(ins)`. To add a worker-set to a tree, call

```
bool NrcWorkerSetTreeAddWorkerSet(NRC_WORKER_SET_TREE wst,
    NRC_WORKER_SET ws, NRC_WORKER_SET *incompatible_ws);
```

This will search *wst* for the unique appropriate place to insert *ws*, returning `true` and inserting *ws* there if that place exists, and returning `false` and not inserting *ws* otherwise. In the latter case, **incompatible_ws* is set to an incompatible worker-set, one which prevents insertion of *ws* because *ws* and **incompatible_ws* are not disjoint, and nor is either a subset of the other.

To visit the worker-sets stored in the root of worker-set tree *wst*, call

```
int NrcWorkerSetTreeRootWorkerSetCount(NRC_WORKER_SET_TREE wst);
NRC_WORKER_SET NrcWorkerSetTreeRootWorkerSet(NRC_WORKER_SET_TREE wst,
    int i);
```

as usual. To visit the children of *wst*, call

```
int NrcWorkerSetTreeChildCount(NRC_WORKER_SET_TREE wst);
NRC_WORKER_SET_TREE NrcWorkerSetTreeChild(NRC_WORKER_SET_TREE wst,
    int i);
```

in the usual way. The tree lies in its instance's arena and will be freed when its instance is freed. Finally,

```
void NrcWorkerSetTreeDebug(NRC_WORKER_SET_TREE wst, int indent, FILE *fp);
```

produces a debug print of *wst* onto *fp* with the given indent.

3.9. Constraints

A *constraint* is a rule which constrains a solution. If the rule is violated by some solution, a cost is added to the solution's cost. The cost of a solution is the total cost of all constraint violations.

A constraint may be *hard*, meaning that any cost is added to a total called the *hard cost*, or *soft*, meaning that it is added to a total called the *soft cost*. So the cost of a solution is actually this pair of values. A solution with non-zero hard cost is often considered infeasible.

In nurse rostering there are two kinds of constraints: *demand constraints* (often called *cover constraints*), which specify the numbers and skills of workers needed by shifts, and *worker constraints*, which give rules that the timetables of individual workers must follow: a limit on the number of shifts worked, no morning shift on the day after a night shift, and so on. Both kinds are described in this section, although in the NRC model they are not closely related.

3.9.1. Penalties and costs

The cost of a violation of a constraint is a function of two things: the *degree of violation* of the constraint, also called the *deviation*, and the *penalty* associated with the constraint.

Most constraints are not simply violated or not; rather, they are violated to some degree. For example, if some constraint requires worker Smith to work at most 18 shifts, the degree of violation is the amount by which the number of shifts Smith works exceeds 18, or 0 if it does not. The degree of violation is always a non-negative integer.

The *penalty* is a triple of values: *hard*, a Boolean value which is true when the constraint is hard, and false when it is soft (in NRC, every constraint can be hard or soft); *weight*, a non-negative integer; and *cost_fn*, a value of type

```
typedef enum {
    NRC_COST_FUNCTION_STEP,
    NRC_COST_FUNCTION_LINEAR,
    NRC_COST_FUNCTION_QUADRATIC
} NRC_COST_FUNCTION;
```

Let the degree of violation (a non-negative number) be x . When $x = 0$, the cost is 0. When $x > 0$, the cost depends on the cost function. When *cost_fn* is `NRC_COST_FUNCTION_STEP` it is w , the penalty weight. When *cost_fn* is `NRC_COST_FUNCTION_LINEAR` (the usual value) the cost is wx . When *cost_fn* is `NRC_COST_FUNCTION_QUADRATIC` the cost is wx^2 . This cost is added to the total hard cost or soft cost, depending on whether *hard* is true or false.

A penalty is represented by a non-NULL value of type `NRC_PENALTY`. It would ordinarily be created by a function called `NrcPenaltyMake`, but a briefer name has been chosen in this case:

```
NRC_PENALTY NrcPenalty(bool hard, int weight,
    NRC_COST_FUNCTION cost_fn, NRC_INSTANCE ins);
```

A negative weight causes `NrcPenalty` to abort, while if `weight > 1000`, it is silently reduced to 1000 (the largest legal XESTT weight). Also, if `weight == 0`, *hard* is silently set to false and *cost_fn* to `NRC_COST_FUNCTION_LINEAR`. To create a penalty with weight zero, it may be easier to call `NrcInstanceZeroPenalty` (Section 3.3.1) than to make a fresh one using `NrcPenalty`.

The attributes of a penalty may be retrieved by calls to

```
bool NrcPenaltyHard(NRC_PENALTY p);
int NrcPenaltyWeight(NRC_PENALTY p);
NRC_COST_FUNCTION NrcPenaltyCostFn(NRC_PENALTY p);
```

as usual. There is also

```
bool NrcPenaltyEqual(NRC_PENALTY p1, NRC_PENALTY p2);
```

which returns true when p1 and p2 have equal attributes.

To help with debugging, function

```
char *NrcPenaltyShow(NRC_PENALTY p, HA_ARENA a);
```

displays the penalty as a string, for example "hard:10:quadratic", stored in arena a. When the cost function is NRC_COST_FUNCTION_LINEAR, the third part is omitted.

3.9.2. Bounds

A *bound* is a set of integer minimum or maximum limits, together with penalties which are to be applied when the value of some quantity (not specified by the bound itself) falls short of a minimum limit or exceeds a maximum limit. Together, these define a function which maps each non-negative value of the quantity to a non-negative cost.

For several good reasons, bounds are not as general as they could be. For example, they do not implement arbitrary piecewise linear functions. Instead, they focus on things needed in practice. To create a bound which initially limits nothing (defining the zero function), call

```
NRC_BOUND NrcBoundMake(NRC_INSTANCE ins);
```

To add a minimum, maximum, or preferred limit to a bound, call

```
bool NrcBoundAddMin(NRC_BOUND b, int min_value, bool allow_zero,
    NRC_PENALTY below_min_penalty);
bool NrcBoundAddMax(NRC_BOUND b, int max_value,
    NRC_PENALTY above_max_penalty);
bool NrcBoundAddPreferred(NRC_BOUND b, int preferred_value,
    NRC_PENALTY below_preferred_penalty,
    NRC_PENALTY above_preferred_penalty);
```

Each of these functions can be called at most once on a given bound b. Each returns true when the limit is consistent with all other limits previously added to b.

NrcBoundAddMin says that if the value x of the quantity being limited is below min_value, then penalty below_min_penalty applies to min_value - x. When allow_zero is true, if x is 0, then, as a special case, no penalty applies.

NrcBoundAddMax says that if the value x of the quantity being limited is above max_value, then penalty above_max_penalty applies to x - max_value.

NrcBoundAddPreferred says that if the value x is below preferred_value, then penalty below_preferred_penalty applies to preferred_value - x, while if it is above

preferred_value, then above_preferred_penalty applies to $x - \text{preferred_value}$.

When there is both a minimum value and a maximum value, false is returned if the maximum value is less than the minimum value.

When there is both a minimum and a preferred value, false is returned if the preferred value is smaller than the minimum value. The preferred penalty applies from the preferred value exclusive down to the minimum value inclusive. This interval is empty when the preferred value equals the minimum value. Below the minimum value, only the minimum penalty applies.

When there is both a maximum and a preferred value, false is returned if the preferred value is larger than the maximum value. The preferred penalty applies from the preferred value exclusive up to the maximum value inclusive. This interval is empty when the preferred value equals the maximum value. Above the maximum value, only the maximum penalty applies.

A preferred limit is not just a minimum limit plus a maximum limit; it applies with lower priority than a minimum or maximum limit, as can be seen when its value is equal to a minimum or maximum limit. This is one of the good reasons why the bound type is not more general.

There is one last rule. When there is both a preferred limit and a maximum limit, both penalties must be linear, and the weight of the maximum penalty must be substantially larger than the weight of the preferred penalty (for how much larger, see below.) As usual, false is returned when these conditions do not hold. A corresponding rule applies when there is both a preferred limit and a minimum limit.

This rule is made because, above the maximum limit, both constraints will be violated in XESTT, whereas in a bound, only the maximum penalty applies. (This is to agree with the Curtois original instances.) Accordingly, the weight of the maximum penalty must be reduced by the weight of the preferred penalty, and a constant adjustment must be added, using a constraint with a step cost function. The Appendix to this section has the details.

For convenience, there are also functions that make a bound object and add one limit to it:

```
NRC_BOUND NrcBoundMakeMin(int min_value, bool allow_zero,
    NRC_PENALTY below_min_penalty, NRC_INSTANCE ins);
NRC_BOUND NrcBoundMakeMax(int max_value,
    NRC_PENALTY above_max_penalty, NRC_INSTANCE ins);
NRC_BOUND NrcBoundMakePreferred(int preferred_value,
    NRC_PENALTY below_preferred_penalty,
    NRC_PENALTY above_preferred_penalty, NRC_INSTANCE ins);
```

The first limit cannot be inconsistent, so these functions do not need to return a Boolean result. Further limits may be added as usual. And functions

```
bool NrcBoundMin(NRC_BOUND b, int *min_value, bool *allow_zero,
    NRC_PENALTY *below_min_penalty);
bool NrcBoundMax(NRC_BOUND b, int *max_value,
    NRC_PENALTY *above_max_penalty);
bool NrcBoundPreferred(NRC_BOUND b, int *preferred_value,
    NRC_PENALTY *below_preferred_penalty,
    NRC_PENALTY *above_preferred_penalty);
```

return true when a minimum, maximum, or preferred limit has been added to b, setting the other parameters to its attributes if so. Finally, to display a bound for debugging there is

```
char *NrcBoundShow(NRC_BOUND b);
```

The result is stored in static memory and will be overwritten by the next call to NrcBoundShow.

Appendix. Here is what needs to be done when there is both a preferred limit and a maximum limit. We assume that both penalties are linear, and that either both are hard or both are soft. The desired penalty function is

$$\begin{aligned} f(x) &= 0 & x \leq x_1 \\ &= w_1(x - x_1) & x_1 < x \leq x_2 \\ &= w_2(x - x_2) & x_2 < x \end{aligned}$$

where x_1 is the preferred limit, w_1 is the penalty weight for exceeding x_1 , x_2 is the maximum limit, w_2 is the penalty weight for exceeding x_2 , and x , x_1 , and x_2 are integers.

We can't just use the obvious two constraints, because the cost will be $w_1(x - x_1) + w_2(x - x_2)$ for $x_2 < x$, not $w_2(x - x_2)$. Our first attempt at a fix is to reduce w_2 by w_1 to compensate, giving

$$\begin{aligned} g_1(x) &= 0 & x \leq x_1 \\ &= w_1(x - x_1) & x_1 < x \leq x_2 \\ &= w_1(x - x_1) + (w_2 - w_1)(x - x_2) & x_2 < x \end{aligned}$$

This is implementable with two constraints. The first two parts are correct, but the third is

$$\begin{aligned} w_1(x - x_1) + (w_2 - w_1)(x - x_2) &= w_1x - w_1x_1 + w_2(x - x_2) - w_1x + w_1x_2 \\ &= w_2(x - x_2) + w_1(x_2 - x_1) \end{aligned}$$

which differs from the needed $w_2(x - x_2)$ by the constant value $w_1(x_2 - x_1)$.

A constant can be compensated for using a constraint with a step cost function; but $w_1(x_2 - x_1)$ is positive, so the weight would need to be negative, which is not allowed. To fix this problem, we start the second constraint from $x_2 + 1$ rather than x_2 :

$$\begin{aligned} g_2(x) &= 0 & x \leq x_1 \\ &= w_1(x - x_1) & x_1 < x \leq x_2 + 1 \\ &= w_1(x - x_1) + (w_2 - w_1)(x - (x_2 + 1)) & x_2 + 1 < x \end{aligned}$$

Now the third part is

$$\begin{aligned} w_1(x - x_1) + (w_2 - w_1)(x - (x_2 + 1)) &= w_1x - w_1x_1 + w_2x - w_2x_2 - w_2 - w_1x + w_1x_2 + w_1 \\ &= w_2(x - x_2) + w_1(x_2 - x_1 + 1) - w_2 \end{aligned}$$

which gives a negative constant as desired, provided w_2 is sufficiently large. This leads to

$$\begin{aligned}
g_3(x) &= 0 & x \leq x_1 \\
&= w_1(x - x_1) & x_1 < x \leq x_2 + 1 \\
&= w_1(x - x_1) + (w_2 - w_1)(x - (x_2 + 1)) + (w_2 - w_1)(x_2 - x_1 + 1) & x_2 + 1 < x
\end{aligned}$$

However, there is now a problem at $x = x_2 + 1$: we have $f(x_2 + 1) = w_2(x_2 + 1 - x_2) = w_2$, whereas $g_3(x_2 + 1) = w_1(x_2 + 1 - x_1)$. But this can be fixed by including $x_2 + 1$ in the step, giving

$$\begin{aligned}
g_4(x) &= 0 & x \leq x_1 \\
&= w_1(x - x_1) & x_1 < x \leq x_2 \\
&= w_1(x - x_1) + (w_2 - w_1)(x_2 - x_1 + 1) & x_2 < x \leq x_2 + 1 \\
&= w_1(x - x_1) + (w_2 - w_1)(x_2 - x_1 + 1) + (w_2 - w_1)(x - (x_2 + 1)) & x_2 + 1 < x
\end{aligned}$$

This is implementable by three constraints: a linear constraint with maximum limit x_1 and weight w_1 ; a step constraint with maximum limit x_2 and weight $w_2 - w_1(x_2 - x_1 + 1)$; and a linear constraint with maximum limit $x_2 + 1$ and weight $w_2 - w_1$.

As a final check, we verify that $g_4(x) = f(x)$. For $x \leq x_1$, both functions are 0. For $x_1 < x \leq x_2$, both functions are $w_1(x - x_1)$. For $x_2 < x \leq x_2 + 1$, that is, for $x = x_2 + 1$, we have $f(x) = f(x_2 + 1) = w_2(x_2 + 1 - x_2) = w_2$, while $g_4(x) = w_1(x_2 + 1 - x_1) + (w_2 - w_1)(x_2 - x_1 + 1) = w_2$. Finally, for $x_2 + 1 < x$, we have $f(x) = w_2(x - x_2)$, while

$$\begin{aligned}
g_4(x) &= w_1(x - x_1) + (w_2 - w_1)(x_2 - x_1 + 1) + (w_2 - w_1)(x - (x_2 + 1)) \\
&= w_1x - w_1x_1 + w_2 - w_1x_2 + w_1x_1 - w_1 + w_2(x - x_2) - w_2 - w_1x + w_1x_2 + w_1 \\
&= w_2(x - x_2)
\end{aligned}$$

So there we are.

There are a few obvious special cases. When $x_1 = x_2$, replacing x_1 by x_2 in $f(x)$ gives

$$\begin{aligned}
f(x) &= 0 & x \leq x_2 \\
&= w_1(x - x_2) & x_2 < x \leq x_2 \\
&= w_2(x - x_2) & x_2 < x
\end{aligned}$$

The second case is empty, so this reduces to a single constraint; the preferred limit can be ignored. This is true for all penalty functions. When the weight given above for the step constraint is negative, that constraint cannot be implemented and this conversion fails. When it is 0 the step constraint can be omitted as usual.

Essentially the same analysis applies when there is both a minimum limit and a preferred limit. Assume for now that `allow_zero` is not requested. The desired penalty function is

$$\begin{aligned}
f(x) &= 0 & x \geq x_1 \\
&= w_1(x_1 - x) & x_1 > x \geq x_2 \\
&= w_2(x_2 - x) & x_2 > x
\end{aligned}$$

where x_1 is the preferred limit, w_1 is the penalty weight for falling short of x_1 , x_2 is the minimum limit, w_2 is the penalty weight for falling short of x_2 , and x , x_1 , and x_2 are integers. Function

$$\begin{aligned}
 h_4(x) &= 0 && x \geq x_1 \\
 &= w_1(x_1 - x) && x_1 > x \geq x_2 \\
 &= w_1(x_1 - x) + (w_2 - w_1(x_1 - x_2 + 1)) && x_2 > x \geq x_2 - 1 \\
 &= w_1(x_1 - x) + (w_2 - w_1(x_1 - x_2 + 1)) + (w_2 - w_1)((x_2 - 1) - x) && x_2 - 1 > x
 \end{aligned}$$

does the trick. It is implementable by three constraints: a linear constraint with minimum limit x_1 and weight w_1 ; a step constraint with minimum limit x_2 and weight $w_2 - w_1(x_1 - x_2 + 1)$; and a linear constraint with minimum limit $x_2 - 1$ and weight $w_2 - w_1$.

Constraints with 0 limits are dropped before applying this formula. Even then, $x_2 - 1 = 0$ is possible, in which case the third constraint does nothing and is omitted.

It does not matter whether or not the preferred limit requests `allow_zero`, because it is overridden by the minimum limit. If the minimum limit requests `allow_zero`, that is easily handled by requesting `allow_zero` in each generated constraint.

A different approach to the general problem of multiple limits would be to extend XESTT to allow cost functions which are arbitrary piecewise step, linear and quadratic functions. However, that would substantially increase the complexity of XESTT for the sake of an uncommon case which adds very little, considered from the point of view of the institution being modelled.

In instance file `Musa.ros`, lines 306 and 453 form a case where there is a minimum value and a preferred value, with $x_1 = 3$, $w_1 = 5$, $x_2 = 1$, and $w_2 = 7$. This fails the formula given above, but it is somewhat illogical, because it gives values $f(3) = 0$, $f(2) = 5$, $f(1) = 10$, and $f(0) = 7$. Rather than reject the instance, NRCConv chooses to ignore the minimum limit (with a warning message) and carry on. `Musa.ros` contains 14 essentially identical instances of this problem.

3.9.3. Demands

A *demand* is an object of type `NRC_DEMAND`, defining a request for one worker to be assigned to an unspecified shift, and associated penalties for when the assignment is defective.

A demand is created by a call to

```

NRC_DEMAND NrcDemandMake(NRC_INSTANCE ins,
    NRC_PENALTY not_assigned_penalty, NRC_PENALTY assigned_penalty,
    NRC_WORKER_SET preferred_ws, NRC_PENALTY not_preferred_penalty);

```

This returns an existing object with these attributes if there is one, otherwise it returns a new one. Returning an existing object is quite safe, because demand objects are immutable, and doing it this way helps the implementation to optimize the length of the generated file.

In a solution, penalty `not_assigned_penalty` is incurred if a worker is not assigned to satisfy this demand. Penalty `assigned_penalty` is incurred if a worker *is* assigned to satisfy this demand. If a worker not in `preferred_ws` is assigned (but not if no worker is assigned), penalty `not_preferred_penalty` is incurred.

Penalties with weight 0 may be passed to `NrcDemandMake`. The penalty for assigning

an unpreferred worker may vary from one worker to another, so `not_preferred_penalty` is a default value, used when some worker not in `preferred_ws` is assigned, but `NrcWorkerAddSkillPenalty` (Section 3.8) has not been called to associate a penalty with that worker. Passing `NULL` for `preferred_ws` is the way to omit this constraint, not passing `NULL` for `not_preferred_penalty`.

Adding a demand to a shift is a separate step, done by `NrcShiftAddDemand` (Section 3.7.1). The same demand object may be added any number of times to one shift, or to several shifts.

Some models specify an optimum number of workers but no maximum. For these it is necessary to fix on some maximum (twice the optimum, perhaps), and pass that many demands, some, perhaps, with assignment penalties. This necessity arises because the XESTT model requires that each event contain a definite fixed number of event resources.

The attributes of a demand object may be retrieved by calling

```
NRC_INSTANCE NrcDemandInstance(NRC_DEMAND d);
NRC_PENALTY NrcDemandNotAssignedPenalty(NRC_DEMAND d);
NRC_PENALTY NrcDemandAssignedPenalty(NRC_DEMAND d);
NRC_WORKER_SET NrcDemandPreferredWorkerSet(NRC_DEMAND d);
NRC_PENALTY NrcDemandNotPreferredPenalty(NRC_DEMAND d);
```

Function

```
void NrcDemandDebug(NRC_DEMAND d, int indent, FILE *fp);
```

produces a debug print of `d` onto `fp`, as explained in Section 3.2.

3.9.4. Demand-sets

Demand-sets are sets of demands, defined in the usual way:

```
NRC_DEMAND_SET NrcDemandSetMake(NRC_INSTANCE ins);
NRC_INSTANCE NrcDemandSetInstance(NRC_DEMAND_SET ds);
void NrcDemandSetAddDemand(NRC_DEMAND_SET ds, NRC_DEMAND d);
```

There is also the trivial helper function

```
void NrcDemandSetAddDemandMulti(NRC_DEMAND_SET ds, NRC_DEMAND d,
    int multiplicity);
```

which calls `NrcDemandSetAddDemand(ds, d)` `multiplicity` times. It is quite normal for one demand object to be added to a demand set multiple times, this way or otherwise; it just means that that many identical demands are being made.

Demand-sets make it easy to build up the total requirements for one shift into a single object. For example, here is the author's original code for constructing a suitable demand-set for shifts in the Second International Nurse Rostering Competition:


```

p1 = NrcPenalty(true, 1, NRC_COST_FUNCTION_LINEAR, ins);
p2 = NrcPenalty(false, 30, NRC_COST_FUNCTION_LINEAR, ins);
p3 = NrcPenalty(false, 0, NRC_COST_FUNCTION_LINEAR, ins);
dms = NrcDemandSetMake(ii->ins);
dm = NrcDemandMake(ii->ins, p1, p3, ws, p1);
NrcDemandSetAddDemandMulti(dms, dm, min_cover);
dm = NrcDemandMake(ii->ins, p2, p3, ws, p1);
NrcDemandSetAddDemandMulti(dms, dm, opt_cover - min_cover);
dm = NrcDemandMake(ii->ins, p3, p3, ws, p1);
NrcDemandSetAddDemandMulti(dms, dm, opt_cover);

```

The demand-set contains `min_cover` demands for which non-assignment incurs a hard penalty, `opt_cover - min_cover` demands for which non-assignment incurs a soft penalty, and `opt_cover` demands for which non-assignment incurs no penalty. All demands include a hard penalty for assigning a worker without the required skill.

In the example just given, the minimum and optimum cover are reminiscent of a bound (Section 3.9.2) with minimum and preferred limits. This function develops this idea:

```

NRC_DEMAND_SET NrcDemandSetMakeFromBound(NRC_INSTANCE ins,
    NRC_BOUND b, int count, NRC_WORKER_SET preferred_ws,
    NRC_PENALTY not_preferred_penalty);

```

It returns a set of `count` demands, all with `preferred_ws` and `not_preferred_penalty`. Each `not_assigned_penalty` and `assigned_penalty` attribute is either one of the penalties in the bound or else is zero (has weight 0). It would be too tedious to describe all the cases. But, as an example, suppose that minimum, preferred, and maximum values are present in the bound. Then the first `min_value` demands have `below_min_penalty` for `not_assigned_penalty` and zero for `assigned_penalty`; the next `preferred_value - min_value` demands have `below_preferred_penalty` for `not_assigned_penalty` and zero for `assigned_penalty`; the next `max_value - preferred_value` demands have zero for `not_assigned_penalty` and `above_preferred_penalty` for `assigned_penalty`; and the last `count - max_value` demands have zero for `not_assigned_penalty` and `above_max_penalty` for `assigned_penalty`. All these penalties must be linear, and any `allow_zero` attribute must be false.

For example, the following code is equivalent to the code above:

```

p1 = NrcPenalty(true, 1, NRC_COST_FUNCTION_LINEAR, ins);
p2 = NrcPenalty(false, 30, NRC_COST_FUNCTION_LINEAR, ins);
p3 = NrcPenalty(false, 0, NRC_COST_FUNCTION_LINEAR, ins);
b = NrcBoundMakeMin(min_cover, false, p1);
NrcBoundAddPreferred(b, opt_cover, p2, p3);
dms = NrcDemandSetMakeFromBound(ins, b, opt_cover * 2, ws, p1);

```

It is shorter, but the important thing is that it is easier to use. To add a maximum cover, for example, just add a maximum value to the bound.

Demand sets are traversed in the usual way:

```
int NrcDemandSetDemandCount(NRC_DEMAND_SET ds);
NRC_DEMAND NrcDemandSetDemand(NRC_DEMAND_SET ds, int i);
```

They retain no memory of how their demands were added. Function

```
void NrcDemandSetDebug(NRC_DEMAND_SET ds, int indent, FILE *fp);
```

produces a debug print of `ds` onto `fp`, as explained in Section 3.2.

3.9.5. Demand constraints

The usual way to specify the workers required by shifts is to add demands to the shifts, as just explained. However, some constraints (notably in the Curtois original instances) apply to the whole set of workers that attend some shift, or even to the set of workers that attend a set of shifts (when the constraint is on the workers that attend during some time period). In some cases these constraints can be decomposed into constraints on individual demands, but not always.

For these awkward cases an alternative approach is offered. First, specify a maximum number of workers that may be assigned to each shift, using unconstrained demands like this:

```
dms = NrcDemandSetMake(ins);
p = NrcPenaltyMake(false, 0, NRC_COST_FUNCTION_LINEAR);
dm = NrcDemandMake(ins, p, p, NULL, p);
NrcDemandSetAddDemandMulti(dms, dm, total_cover);
NrcShiftAddDemandSet(s, dms);
```

or equivalently like this:

```
dms = NrcDemandSetMakeFromBound(ins, NrcBoundMake(ins), total_cover,
    NULL, NULL);
NrcShiftAddDemandSet(s, dms);
```

This ensures that shift `s` can be assigned up to `total_cover` workers, without any constraint on how many assignments there should be, or on the assigned workers' skills. Second, call

```
NRC_DEMAND_CONSTRAINT NrcDemandConstraintMake(NRC_BOUND b,
    NRC_SHIFT_SET ss, NRC_WORKER_SET ws, char *name);
```

This adds a constraint to `ss`'s instance which limits the total number of demands from an arbitrary set of shifts that may be assigned workers from a given set. Functions

```
NRC_BOUND NrcDemandConstraintBound(NRC_DEMAND_CONSTRAINT dc);
NRC_SHIFT_SET NrcDemandConstraintShiftSet(NRC_DEMAND_CONSTRAINT dc);
NRC_WORKER_SET NrcDemandConstraintWorkerSet(NRC_DEMAND_CONSTRAINT dc);
char *NrcDemandConstraintName(NRC_DEMAND_CONSTRAINT dc);
```

retrieve the four attributes of demand constraint `dc`.

Parameter `b` is a bound object (Section 3.9.2) which specifies any combination of minimum, maximum, or preferred limits on the number of assignments. It may be a freshly created object with no limits when passed to `NrcDemandConstraintMake`; the limits may be added to it later.

Parameter *ss* is the set of shifts whose assignments are being constrained. For example, if the constraint is on a single shift *s*, then *ss* would be `NrcShiftSingletonShiftSet(s)`.

Parameter *ws* is the set of workers. The constraint is only interested in assignments of these workers; assignments of other workers do not influence it. If the constraint is on the total number of assignments irrespective of skill, then *ws* would be `NrcInstanceStaffing(ins)`.

Parameter *name* does not influence the meaning of the constraint; rather, it helps to identify the constraint in evaluation prints. It does not have to be unique. It should indicate what is being constrained but not the actual limits, because NRC adds that information to the name.

In general, NRC demand constraints are converted into XESTT limit resources constraints. However, where possible, the conversion is to assign resource constraints, since they are simpler in principle (they constrain each event resource independently), a fact which can have practical consequences (e.g. in time sweep assignment algorithms). Assign resource constraints are used for each demand constraint whose worker-set is the entire staffing, and which constrains just one shift, with that shift constrained by no other demand constraints.

3.9.6. Patterns

Patterns are used in several nurse rostering models to say that some sequences of shift types—a morning shift following a night shift, for example—should be forbidden, or penalized.

Given that a worker takes at most one shift per day, the choices on each day are one of its shifts or nothing. Denote the shift types by 1, 2, and 3, and denote the absence of a shift (a free day) by 0. Using regular expression notation, an arbitrary subset of these choices is represented by enclosing them in brackets. For example, `[02]` means ‘a shift of type 2 or nothing.’ In source models, a *pattern* is a sequence of these *terms*, representing the choices on consecutive days. For example, `[3][1]` means ‘an early shift following a night shift’.

A pattern *matches* a worker’s timetable at any day where the worker has a sequence of shifts or days off, each of which matches the corresponding term of the pattern. For example, if a worker’s timetable contains a shift of type 3 on day `1Wed` and a shift of type 1 on day `1Thu`, then pattern `[3][12]` matches that timetable at `1Wed`.

The empty term `[]` is allowed, but it never matches, which makes it useless in practice. On the other hand, `[0123]` says that we don’t care what happens on that day, which can be useful.

NRC supports patterns. A pattern is created by

```
NRC_PATTERN NrcPatternMake(NRC_INSTANCE ins, char *name);
```

where *name* is optional (may be `NULL`). To retrieve the attributes, call

```
NRC_INSTANCE NrcPatternInstance(NRC_PATTERN p);
char *NrcPatternName(NRC_PATTERN p);
```

To add a term to a pattern, call

```
void NrcPatternAddTerm(NRC_PATTERN p, NRC_SHIFT_TYPE_SET sts,
    NRC_POLARITY po);
```

As shown, a term consists of a shift-type set and a *polarity*, of type

```
typedef enum {
    NRC_NEGATIVE,
    NRC_POSITIVE
} NRC_POLARITY;
```

These attributes will be explained shortly. To visit the terms of a pattern, call

```
int NrcPatternTermCount(NRC_PATTERN p);
void NrcPatternTerm(NRC_PATTERN p, int i, NRC_SHIFT_TYPE_SET *sts,
    NRC_POLARITY *po);
```

in the usual way. There is also

```
bool NrcPatternIsUniform(NRC_PATTERN p);
```

which returns true when *p* is *uniform*: when all its terms contain equal shift-type sets and equal polarities. Unwanted patterns can be implemented more efficiently when they are uniform.

Type `NRC_POLARITY` has just one operation:

```
NRC_POLARITY NrcPolarityNegate(NRC_POLARITY po);
```

which returns negative for positive and positive for negative.

A term *t* matches the timetable of worker *w* on day *d* if either *t*'s polarity is `NRC_POSITIVE` and *w* works a shift on day *d* whose type is one of the types of *t*'s shift-type set, or else *t*'s polarity is `NRC_NEGATIVE` and *w* does not work a shift on day *d* whose type is one of the types of *t*'s shift-type set. This second case includes not working at all. A pattern matches *w*'s timetable on day *d* if its first term matches on day *d*, its second term matches on the day after *d*, and so on.

A term which does not contain 0 is represented by a shift-type set containing its shift types, with polarity `NRC_POSITIVE`. A term which contains 0 is represented by a shift-type set containing the complement of the term's non-0 shift types, with polarity `NRC_NEGATIVE`. The reader can easily verify that this does what is wanted. In particular, the don't-care term [0123] is represented by an empty shift-type set with negative polarity. This term always matches.

Creating a pattern does not make it unwanted: it has to be added to a worker constraint, using function `NrcConstraintAddPattern` (Section 3.9.8). The constraint holds information about the cost of violations, and which days the pattern is allowed to match with.

All patterns are stored in the instance, and are accessible by `NrcInstancePatternCount`, `NrcInstancePattern`, and `NrcInstanceRetrievePattern` (Section 3.3.8). Function

```
void NrcPatternDebug(NRC_PATTERN p, int indent, FILE *fp);
```

produces a debug print of *p* onto *fp*, as explained in Section 3.2.

3.9.7. Pattern sets

A *pattern set* is a set of patterns. To make an initially empty pattern set, call

```
NRC_PATTERN_SET NrcPatternSetMake(NRC_INSTANCE ins);
```

Functions

```
NRC_INSTANCE NrcPatternSetInstance(NRC_PATTERN_SET ps);
int NrcPatternSetIndexInInstance(NRC_PATTERN_SET ps);
```

return the pattern set's instance, and its index in the instance.

To add a pattern to a pattern set, call

```
void NrcPatternSetAddPattern(NRC_PATTERN_SET ps, NRC_PATTERN p);
```

This may be done any number of times. To visit the patterns of a pattern set, call

```
int NrcPatternSetPatternCount(NRC_PATTERN_SET ps);
NRC_PATTERN NrcPatternSetPattern(NRC_PATTERN_SET ps, int i);
```

in the usual way.

The function that makes pattern sets non-trivial is

```
NRC_PATTERN_SET NrcPatternSetReduce(NRC_PATTERN_SET ps);
```

This returns a new pattern set whose patterns match at the same points as *ps*'s patterns do, but usually using fewer patterns. To see the use for this, consider this excerpt from one of the recent *Curtois* and *Qu* instances:

```
a4,720,a1|a2|a3|a4|d1|d2|d3|d4|d5
d1,480,a1|a2|a3
d2,480,a1|a2|a3
d3,600,a1|a2|a3|a4
d4,720,a1|a2|a3|a4|d1|d2|d3|d4|d5
```

Ignoring the workload limits, this gives for each shift type (not all are shown here) a list of other shift types that may not follow it, so it defines a set of patterns. The reduced set is

```
a4|d4,720,a1|a2|a3|a4|d1|d2|d3|d4|d5
d1|d2,480,a1|a2|a3
d3,600,a1|a2|a3|a4
```

These patterns match at the same points as the originals, but there are fewer of them, leading to smaller generated instances. The function merges pairs of patterns with the same length and equal elements and polarities except at one place, where the elements must be disjoint and the polarities must be equal.

Instead of building then reducing, it may be simpler to reduce while building, by calling

```
void NrcPatternSetMergePattern(NRC_PATTERN_SET ps, NRC_PATTERN p);
```

It is like `NrcPatternSetAddPattern` except that it first tries to merge *p* into an existing pattern of *ps*, only adding it as a separate pattern as a last resort. Finally,

```
void NrcPatternSetDebug(NRC_PATTERN_SET ps, int indent, FILE *fp);
```

produces a debug print of *ps* in the usual way.

3.9.8. Worker constraints

A *worker constraint* is a constraint on the timetables of individual workers. Worker constraints all seem to have a similar form: they contain a set of shift-sets, and for each worker they determine whether the worker is busy or free during each shift-set, calculate totals of busy and free shift-sets, and assign a penalty proportional to the amount by which the totals fall short of a given minimum limit or exceed a given maximum limit. There are variations: when there is a non-zero minimum limit, in some cases a total of 0 is nevertheless not penalized; sometimes the total workload (measured in minutes, say) is limited rather than the number of shifts; some constraints are repeated along the cycle (every weekend, for example); some apply to sequences of consecutive shift-sets, others are just concerned with totals, not with ordering; and so on. Nevertheless NRC offers a single interface for all worker constraints.

A shift is *busy* for a worker when the worker works that shift. A shift is *free* for a worker when it is not busy for the worker. A shift-set is busy for a worker when at least one of its shifts is busy for the worker. A shift-set is free for a worker when it is not busy for the worker.

When a shift-set is added to a constraint, a polarity (Section 3.9.6) is added with it, saying whether the shift-set is to be treated *positively* or *negatively*. Informally, we say that a shift-set is *positive* when its associated polarity is positive, and *negative* otherwise. However, it is the usage of the shift-set within the constraint which is positive or negative, not the shift-set itself.

When a constraint is applied to a particular worker, a shift-set within it is *active* when it is positive and busy for the worker, or negative and free for the worker. Otherwise it is *inactive*. The constraint calculates the total number of active shift-sets, and compares it with the limits. If all shift-sets are positive, this constrains busy shift-sets; if all are negative, it constrains free shift-sets. Mixtures of positive and negative are legal, and useful for implementing unwanted patterns.

To create a worker constraint, initially with no shift-sets, call

```
NRC_CONSTRAINT NrcConstraintMake(NRC_INSTANCE ins, char *name,
    NRC_WORKER_SET ws, NRC_CONSTRAINT_TYPE type, NRC_BOUND bound,
    NRC_SHIFT_SET starting_ss);
```

This returns a new constraint and also adds it to *ins*. The type should really be called `NRC_WORKER_CONSTRAINT`, but `NRC_CONSTRAINT` is shorter. To retrieve the attributes, call

```
NRC_INSTANCE NrcConstraintInstance(NRC_CONSTRAINT c);
char *NrcConstraintName(NRC_CONSTRAINT c);
NRC_WORKER_SET NrcConstraintWorkerSet(NRC_CONSTRAINT c);
NRC_CONSTRAINT_TYPE NrcConstraintType(NRC_CONSTRAINT c);
NRC_BOUND NrcConstraintBound(NRC_CONSTRAINT c);
NRC_SHIFT_SET NrcConstraintStartingShiftSet(NRC_CONSTRAINT c);
```

Parameter *name* is the name given to XESTT constraints derived from this constraint. A good choice here is an informal source model description, expressed positively, that is, as what is wanted rather than what is to be avoided: "At most 4 busy weekends" and so on. Names mainly appear as entries in tables of defects, where there are other entries giving the details, so a short, informal phrase is best. There is no need for names to be distinct. NRC will ensure that the XESTT constraints it generates have distinct Ids, which is a different thing.

Parameter *ws* says which workers the constraint applies to. For example, *ws* could hold the

workers who share a contract containing this constraint. If the constraint is for a single worker w , then ws is `NrcWorkerSingletonWorkerSet(w)` (Section 3.8.1). Worker constraints which are equal apart from ws are merged by `NrcArchiveWrite` into a single XESTT constraint.

Parameter `type` determines what is constrained, and has type

```
typedef enum {
    NRC_CONSTRAINT_ACTIVE,
    NRC_CONSTRAINT_CONSECUTIVE,
    NRC_CONSTRAINT_WORKLOAD
} NRC_CONSTRAINT_TYPE;
```

`NRC_CONSTRAINT_ACTIVE` means that the constraint is on the number of active shift-sets; `NRC_CONSTRAINT_CONSECUTIVE` means that the constraint is on the number of consecutive active shift-sets;¹ and `NRC_CONSTRAINT_WORKLOAD` means that the constraint is on the total workload of the shifts of one shift-set.

Parameter `bound` says whether the constraint is a minimum limit, a minimum limit in which zero is allowed, or a maximum limit, or a combination, and includes penalties for when the limit is violated (Section 3.9.2).

Lastly, `starting_ss` repeats the constraint along the cycle. If it is `NULL`, the constraint is applied only once. If it is non-`NULL`, the distance from its first shift to each of its other shifts defines a distance along the cycle to repeat the constraint. For example, if `starting_ss` holds the first shift of each day, the constraint repeats on every day. `NrcInstanceDailyStartingShiftSet` and `NrcInstanceWeeklyStartingShiftSet` (Section 3.3.5), `NrcDaySetStartingShiftSet` (Section 3.4.3), and `NrcShiftSetSetStartingShiftSet` (Section 3.7.3) return most of the starting shift-sets needed in practice.

When `starting_ss` is used, the shift-sets added to the constraint must define only the earliest occurrence of the constraint. Some of `starting_ss`'s shifts may place the constraint at points of the cycle where some parts of it go off the end. Such shifts are legal but are ignored.

One may use `starting_ss` with the consecutive limit types, to get constraints such as a limit on the number of consecutive days worked within each four-week interval. But these never seem to occur in source models, perhaps because they are very artificial at the boundaries.

After creating the constraint, add shift-sets to it by calling

```
void NrcConstraintAddShiftSet(NRC_CONSTRAINT c,
    NRC_SHIFT_SET ss, NRC_POLARITY po);
void NrcConstraintAddShiftSetSet(NRC_CONSTRAINT c,
    NRC_SHIFT_SET_SET sss, NRC_POLARITY po);
```

any number of times, arbitrarily intermixed. This adds the shift-sets, each accompanied by a polarity, either one at a time or many at once. There is also

```
void NrcConstraintAddPattern(NRC_CONSTRAINT c, NRC_PATTERN p, NRC_DAY d);
```

A pattern is a sequence of shift-type sets with polarities, and `NrcConstraintAddPattern` simply

¹The author learned of this approach to constraining consecutive subsequences from Gerhard Post.

makes the corresponding sequence of calls to `NrcConstraintAddShiftSet`, converting each shift type set `sts` into a shift set, by calling `NrcDayShiftSetFromShiftTypeSet(d, sts)` for the shift type set of the first term, and similarly using successive days for successive terms.

To visit the shift-sets and polarities added to a constraint `c`, call

```
int NrcConstraintShiftSetCount(NRC_CONSTRAINT c);
void NrcConstraintShiftSet(NRC_CONSTRAINT c, int i,
    NRC_SHIFT_SET *ss, NRC_POLARITY *po);
```

as usual. The constraint does not remember whether the shift-sets and polarities were added individually, or using shift-set sets, or using patterns.

One common form of constraint, the unwanted pattern, is already implemented:

```
NRC_CONSTRAINT NrcUnwantedPatternConstraintMake(NRC_INSTANCE ins,
    char *name, NRC_WORKER_SET ws, NRC_PENALTY penalty, NRC_PATTERN p,
    NRC_DAY_SET starting_ds);
```

The first three parameters and the return value are as for `NrcConstraintMake`. Parameter `penalty` is the penalty to apply when the pattern is violated. The last two parameters give the unwanted pattern and the set of days on which it may begin (pass `NrcInstanceCycle(ins)` if it may begin on any day). Here `p` must contain at least one term, and `starting_ds` must contain at least one day.

Function

```
void NrcConstraintDebug(NRC_CONSTRAINT c, int indent, FILE *fp);
```

produces a debug print of `c` onto `fp`, as explained in Section 3.2.

3.9.9. Examples of worker constraints

this section is out of date, it needs a makeover

This section presents some examples of worker constraints. Many more may be found in the source code. For reference, here is the interface of `NrcConstraintMake` from Section 3.9.8:

```
NRC_CONSTRAINT NrcConstraintMake(NRC_INSTANCE ins, char *name,
    NRC_WORKER_SET ws, NRC_CONSTRAINT_TYPE type, NRC_BOUND bound,
    NRC_SHIFT_SET starting_ss);
```

Let `ins` be an NRC instance. To say that all staff should work at most one shift per day:

```
c = NrcConstraintMake(ins, "Single assignment per day",
    NrcInstanceStaffing(ins), p, NRC_LIMIT_MAX, 1,
    NrcInstanceDailyStartingShiftSet(ins));
NrcConstraintAddShiftSetSet(c,
    NrcDayShiftSetSet(NrcInstanceCycleDay(ins, 0), NRC_POSITIVE);
```

Looking along the arguments of `NrcConstraintMake`, `c` applies to all workers, has penalty `p`, maximum limit 1 (not consecutive), and repeats each day. The second statement defines the first

point where it applies: to the shifts of the first day of the cycle. The shift-set set ensures that each shift is added in its own shift-set, so that the usual limit on the number of busy shift-sets becomes a limit on the number of busy shifts. It would be wrong to pass in a single shift-set containing all the shifts of the day, but NRConv works out that this is a simple case and generates a limit busy times constraint rather than a cluster busy times constraint.

To impose a maximum workload limit of 28 shifts:

```
c = NrcConstraintMake(ins, "At most 28 shifts",
    NrcInstanceStaffing(ins), p, NRC_LIMIT_MAX, 28, NULL);
NrcConstraintAddShiftSetSet(c, NrcInstanceShiftsShiftSetSet(ins),
    NRC_POSITIVE);
```

Here *c* applies to all workers, has penalty *p*, is not consecutive, and does not repeat. The second statement adds each shift, again in its own shift-set.

Making a pattern *p* unwanted is very easy:

```
c = NrcConstraintMake(ins, "Unwanted pattern", NrcInstanceStaffing(ins),
    p, NRC_LIMIT_MAX, NrcPatternTermCount(p) - 1,
    NrcInstanceDailyStartingShiftSet(ins));
NrcConstraintAddPattern(c, p, NrcInstanceCycleDay(ins, 0));
```

The constraint applies to all workers, has penalty *p*, has a maximum limit of one less than the pattern length (not consecutive), and starts afresh each day. The last line adds shift-sets defining the first occurrence of the pattern, beginning on the first day of the cycle.

NRConv offers `NrcUnwantedPatternConstraintMake`, its own implementation of unwanted patterns, documented near the end of Section 3.9.8. It is rather more complex than the code above, mainly because, if the pattern is uniform (has the same shift-set and the same polarity at every term) and may begin on any day, it optimizes by generating a limit active intervals constraint rather than a cluster busy times constraint which repeats on each day:

```

NRC_CONSTRAINT NrcUnwantedPatternConstraintMake(NRC_INSTANCE ins,
char *name, NRC_WORKER_SET ws, NRC_PENALTY penalty, NRC_PATTERN p,
NRC_DAY_SET starting_ds)
{
NRC_CONSTRAINT res; NRC_SHIFT_TYPE_SET sts; NRC_POLARITY po; int i;
NRC_DAY d; NRC_SHIFT_SET ss;

MAssert(NrcPatternTermCount(p) > 0,
"NrcUnwantedPatternConstraintMake: empty pattern");
MAssert(NrcDaySetDayCount(starting_ds) > 0,
"NrcUnwantedPatternConstraintMake: empty starting_ds");
if( NrcDaySetDayCount(starting_ds) == NrcInstanceCycleDayCount(ins)
&& NrcPatternIsUniform(p) )
{
/* uniform pattern, single limit active intervals constraint */
res = NrcConstraintMake(ins, name, ws, penalty,
NRC_LIMIT_MAX_CONSECUTIVE, NrcPatternTermCount(p)-1, NULL);
NrcPatternTerm(p, 0, &sts, &po);
for( i = 0; i < NrcInstanceCycleDayCount(ins); i++ )
{
d = NrcInstanceCycleDay(ins, i);
ss = NrcDayShiftSetFromShiftTypeSet(d, sts);
NrcConstraintAddShiftSet(res, ss, po);
}
}
else
{
/* non-uniform pattern, repeating cluster busy times constraint */
res = NrcConstraintMake(ins, name, ws, penalty, NRC_LIMIT_MAX,
NrcPatternTermCount(p)-1, NrcDaySetStartingShiftSet(starting_ds));
NrcConstraintAddPattern(res, p, NrcDaySetDay(starting_ds, 0));
}
return res;
}

```

This function could be written by an NRC user; it does not use any behind-the-scenes features.

Constraints involving weekends need to know when the weekends are. One way to express this is as a day-set set, each day-set of which contains the days of one weekend, in chronological order. Such a day-set set can be built using NRC's functions for building day-sets and day-set sets, following whatever rule the format uses to define weekends, and shared by all constraints concerning weekends. Assuming that `weekends_dss` is such a day-set set, the following code places a maximum limit of 3 on the number of consecutive weekends that worker `w` can work:

```

NRC_CONSTRAINT c; int i; NRC_DAY_SET ds;
c = NrcConstraintMake(ins, "At most 3 consecutive weekends",
    NrcWorkerSingletonWorkerSet(w), p, NRC_LIMIT_MAX_CONSECUTIVE, 3, NULL);
for( i = 0; i < NrcDaySetSetDaySetCount(weekends_dss); i++ )
{
    ds = NrcDaySetSetDaySet(weekends_dss, i);
    NrcConstraintAddShiftSet(c, NrcDaySetShiftSet(ds), NRC_POSITIVE);
}

```

The constraint applies to w only, has penalty p , has maximum limit 3, and is consecutive. There is one shift-set for each weekend, containing the shifts of that weekend.

3.9.10. Adding history to worker constraints

Some constraints need to be influenced by the history of the workers whose timetables they constrain. This can be done by first calling

```

void NrcConstraintAddHistory(NRC_CONSTRAINT c, int history_before,
    int history_after);

```

once, then

```

void NrcConstraintAddHistoryWorker(NRC_CONSTRAINT c, NRC_WORKER w,
    int value);

```

at most once for each worker w in c 's worker-set. The $history_before$, $history_after$, and $value$ values are the a_i , c_i , and x_i values from Jeff Kingston's paper on history.

Functions `NrcWorkerAddHistory` and `NrcWorkerRetrieveHistory` from Section 3.8.1 make it easy to store history values in workers. However, they do not automatically pass these values on to constraints. Code like this is needed for that:

```

c = NrcConstraintMake(..., ws, ...);
NrcConstraintAddHistory(c, ...);
for( i = 0; i < NrcWorkerSetWorkerCount(ws); i++ )
{
    w = NrcWorkerSetWorker(ws, i);
    if( NrcWorkerRetrieveHistory(w, "WeekendsWorked", &v) && v > 0 )
        NrcConstraintAddHistoryWorker(c, w, v);
}

```

Accordingly, NRC offers helper function

```

void NrcConstraintAddHistoryAllWorkers(NRC_CONSTRAINT c,
    int history_before, int history_after, char *name);

```

whose body is the call to `NrcConstraintAddHistory` plus the loop, with `name` for "WeekendsWorked" and `NrcConstraintWorkerSet(c)` for `ws`. Most cases are best handled by `NrcConstraintAddHistoryAllWorkers`, but when its simple approach is not sufficient, one can fall back on `NrcConstraintAddHistory` and `NrcConstraintAddHistoryWorker`.

History may not be added to a constraint with a starting shift-set. It is just too hard to assign a reasonable meaning to it.

3.10. Solutions

This section describes solutions. A solution is a collection of assignments to the demands of the shifts of one instance. It is a very simple thing, making this a very short section.

To create a new solution for a given instance, call

```
NRC_SOLN NrcSolnMake(NRC_INSTANCE ins, HA_ARENA_SET as);
```

where `as` is as for `NrcInstanceMake`. To retrieve the instance, call

```
NRC_INSTANCE NrcSolnInstance(NRC_SOLN soln);
```

A solution contains an optional description, giving its provenance. To set and retrieve it, call

```
void NrcSolnSetDescription(NRC_SOLN soln, char *description);
char *NrcSolnDescription(NRC_SOLN soln);
```

`NrcSolnDescription` returns `NULL` when there is no description.

A solution also contains an optional running time, giving the time in seconds that it took to find. To set this value and retrieve it, call

```
void NrcSolnSetRunningTime(NRC_SOLN soln, float running_time);
float NrcSolnRunningTime(NRC_SOLN soln);
```

`NrcSolnRunningTime` returns `-1.0` when no running time has been passed, meaning ‘absent’.

A newly created solution does not lie in any archives. To add it to an archive, the user must first ensure that that archive has a solution group, by calling `NrcSolnGroupMake` (Section 2.2). Then the solution may be added to the solution group, by calling `NrcSolnGroupAddSoln`.

Internally, a solution is just a collection of assignments of workers to the demands of shifts. Each demand accepts at most one assignment. To add an assignment, call

```
void NrcSolnAddAssignment(NRC_SOLN soln, NRC_SHIFT s, int i,
    NRC_WORKER w);
```

This assigns `w` to demand `i` of `s`, where $0 \leq i < \text{NrcShiftDemandCount}(s)$. The assignment is in `soln`, not in the instance; the instance does not change. `NrcSolnAddAssignment` aborts if an attempt is made to assign a second worker to the same demand.

To inspect an existing assignment, call

```
NRC_WORKER NrcSolnAssignment(NRC_SOLN soln, NRC_SHIFT s, int i);
```

This returns `NULL` when no assignment has been made. Unassigned demands are acceptable within solutions, although they usually incur a penalty, depending on the demand’s penalties.

Part B

The NRConv Executable

Chapter 4. NRConv and its Converters

This chapter describes NRConv and its converters, passing silently over routine things. The material on each converter assumes that the reader has a detailed knowledge of the source model being converted. For NRConv usage information, type `nrconv` with no arguments.

As a rough guide to the complexity of the code, here are line counts for the C source files:

<i>Lines</i>	<i>Files</i>
5092	<code>coi.c</code> , <code>coi_cover.c</code> , and <code>coi_limit.c</code>
1669	<code>inrc1.c</code>
1464	<code>inrc2.c</code>
1836	<code>cq14.c</code>

The format of the Curtois original instances is considerably more complex than the others.

4.1. Instance models and solution models

NRConv has *instance models* and *solution models*, which define the format of source instances and solutions. Whenever it reads a source instance or solution file, it has already been informed (via the `-i` and `-s` command-line flags) which model the file follows.

An instance model is defined by a text file called an *instance model file*. For example:

```
InstanceSourceFormat: inrc1.xml
Contributor: The organizers of INRC1
Date:
Country:
Description:
Remarks: converted from INRC1 format by NRConv
```

Each line consists of an identifier followed by a colon followed by any number of spaces followed by an optional value. The lines must appear in the order shown.

`InstanceSourceFormat` gives the name of the format in which the source instances which follow this model are expressed. There is a fixed set of valid names, which at present is

```
coi.xml inrc1.xml inrc2.xml cq14.txt
```

but which is easy to expand (see the top of file `ins_model.c`). There is nothing to prevent different instance models from using the same source format.

The remaining lines give values for the metadata fields of each instance. If there is no date, as above, then the date that NRConv runs is substituted. All these fields are to be taken as default values. If an instance contains more informative metadata values, they may replace these ones.

A solution model is defined by a text file called a *solution model file*. For example:

```

SolnSourceFormat: inrc1-soln.xml
LinkageToInstance: internal
LinkageToSolnGroup: first
Keep: best
SolnGroup: GOAL
Contributor: The GOAL team
Date:
Description:
Publication: http://www.goal.ufop.br/nrp/
Remarks: converted from INRC1 format by NRConv

```

As before, each line consists of an identifier followed by a colon followed by any number of spaces followed by an optional value, and the lines must appear in the order shown.

The `SolnSourceFormat` line gives the name of the format in which the source solutions are expressed. There is a fixed set of valid names, which at present is

```

coi-soln.xml inrc1-soln.xml inrc2-soln.xml cq14-soln.xml

```

but which is easy to expand (see the top of file `soln_model.c`). There is nothing to prevent different solution models from using the same source format.

The `LinkageToInstance` line defines how to determine which instance a solution is for. Its value may be `internal`, meaning that the solution file contains this information, or `external`, meaning that it doesn't. In the latter case, the longer form of the `-s` command line flag must be used to supply this information.

The `LinkageToSolnGroups` line defines how to determine which solution group a solution should go into. There is a fixed set of values for this, which at present is

```

first cq14

```

but which could expand in the future. Value `first` places each solution into the first solution group defined in this file (which would usually be the only one), while `cq14` uses a complex rule based on the values of the `<Algorithm>` and `<CpuTime>` elements of the solution files.

The `Keep` line says how many solutions to keep for each instance in each solution group. Acceptable values are `all` to keep all solutions, and `best` to keep only one solution, the best.

The `SolnGroup` line defines a solution group with the given name, which will be added to the archive. The following lines define its metadata fields. They must all be present, in the order shown. If there is already a solution group with the given name, it is not added again, but `NRConv` checks that it has the same metadata values as the ones given here, and aborts if not.

To include multiple solution groups, start again after `Remarks` with another `SolnGroup` line, and so on. Every solution goes into exactly one solution group, so if there are any solutions at all, there must be at least one solution group.

4.2. The Curtois original instances

Curtois pioneered the assembly of instances from around the world, and their expression in a common format. Published at

<http://www.cs.nott.ac.uk/~psztc/NRP/>

under the heading ‘Original instances’, there are 28 of these instances, with 66 solutions. Following Curtois, we omit instance HED01b (it is very similar to instance HED01) and its solution, so the converter converts 27 instances and 65 solutions, to archive COI, using instance source format `coi.xml` and solution source format `coi-soln.xml`, which are implemented by functions in NRConv source files `coi.c`, `coi_limit.c`, and `coi_cover.c`.

Instances `ERMGH.ros`, `CHILD.ros`, `ERRVH.ros`, and `MER.ros` use the `<TimePeriod>` feature, which gives cover requirements for periods of the day rather than for each shift type. Several other instances contain multiple cover requirements (for particular skills) which apply to the same shifts. Accordingly, for all the Curtois original instances generally, NRConv produces a generous number of extra event resources (the exact number is documented in `coi_cover.c`), and constrains them using limit resources constraints.

The exception is shifts for which the `<AutoAllocate>` attribute is `false`, meaning that the shift can only be preassigned, not assigned by a solver. Each such shift is given the exact number of event resources required to hold the preassignments, and these event resources are preassigned in the generated instance.

All instances use *pattern constraints* (element `<Match>`), which place minimum and maximum limits on the number of occurrences of the elements of an arbitrary set of patterns. These are not convertible in general. NRConv analyses them into three convertible cases, and omits instances with constraints outside these cases (none of the 27 instances is omitted).

Case 1. The pattern constraint has maximum limit 0 but is otherwise arbitrary. Then the patterns within this constraint are unwanted patterns and are handled as such.

Case 2. Each pattern of the constraint either contains a single term, or a sequence of terms all containing 0, or it is one of the last three patterns, and these together match busy weekends, as in `Sat:[123][123]`, `Sat:[0][123]`, and `Sat:[123][0]`, assuming three shifts per day. The constraint is otherwise arbitrary. It is converted to a resource constraint whose minimum and maximum limits are those of the pattern constraint, and whose time groups express its terms.

A pattern containing a single term is easily expressible using one time group for each starting day. For example, `[12]` is converted to

```
{1Mon1, 1Mon2}
{1Tue1, 1Tue2}
{1Wed1, 1Wed2}
...
```

and these time groups are added to the resource constraint.

A pattern whose terms all contain 0 is converted to one negative time group for each starting day. Consider limiting the number of free weekends, counting a Friday night shift (shift 3) as part of the following weekend. The pattern is `Fri:[012][0][0]`. The time groups are

```
{1Fri3, 1Sat1, 1Sat2, 1Sat3, 1Sun1, 1Sun2, 1Sun3}*
{2Fri3, 2Sat1, 2Sat2, 2Sat3, 2Sun1, 2Sun2, 2Sun3}*
...
```

Each time group contains the complement of each term, on successive days.

Patterns which match busy weekends are easily represented by positive time groups

```
{1Sat1, 1Sat2, 1Sat3, 1Sun1, 1Sun2, 1Sun3}
{2Sat1, 2Sat2, 2Sat3, 2Sun1, 2Sun2, 2Sun3}
```

and so on. NRConv looks for this exact case; it does not attempt to generalize it in any way.

Case 3. NRConv is hard-wired to generate certain XESTT constraints when it reaches certain file positions. This allows it to handle source constraints that fall outside the cases above but which are nevertheless convertible. For example, the pattern constraints at lines 107–148 of `ERMGH.ros` penalize cases of two consecutive busy weekends. The instance begins on a Sunday and ends on a Saturday, and the constraint for the last two weekends does not fit the cases given above, so NRConv generates a hard-wired limit active intervals constraint for the whole set. As it turns out, every hard-wired case except the one for instance `HED01.ros` described below concerns limiting the number of consecutive busy weekends, to one, two, or three.

An awkward pattern constraint occurs at line 95 of instance `ORTEC02.ros`. The problem patterns, `Sat:[NEDL][NEDL]`, `Sat:[0][NEDL]`, and `Sat:[NEDL][0]`, aim to match busy weekends, but they omit the ‘on vacation’ shift `V`, so they leave some busy weekends (`Sat:DV`, for example) unmatched. They should be `Sat:[NEDL][NEDL]`, `Sat:[0V][NEDL]`, and `Sat:[NEDL][0V]`, which are convertible, and in fact they are equivalent to them because the vacation shift can only be preassigned to a nurse, not assigned by the solver, and a hand check shows that cases like `Sat:DV` cannot arise. So the conversion is hard-wired here.

Instance `HED01.ros` (and also the omitted `HED01b.ros`) utilizes *conditional constraints*, which require one pattern to match if another does. These cannot be converted in general, but those in these instances can be. For example, some require all the shifts taken by a nurse in Week 1 to have the same type, which is expressible by a cluster busy times constraint with maximum limit 1 and time groups

```
{1Mon1, 1Tue1, 1Wed1, 1Thu1, 1Fri1, 1Sat1, 1Sun1}
{1Mon2, 1Tue2, 1Wed2, 1Thu2, 1Fri2, 1Sat2, 1Sun2}
{1Mon3, 1Tue3, 1Wed3, 1Thu3, 1Fri3, 1Sat3, 1Sun3}
```

Again, NRConv is hard-wired to generate suitable constraints at these file positions.

The Curtois original instances have undocumented features (such as `<Preferred>` limits alongside `<Min>` and `<Max>`, `<CoverWeights>`, and the format of the `<CpuTime>` attribute of solutions) and undocumented interactions (such as how `<DateSpecificCover>` overrides `<DayOfWeekCover>`). Explaining them all is beyond our scope. There are also documented features which do not appear in the instances. For the most part these are not implemented; NRC will print warning messages and omit instances that contain them.

4.3. The First International Nurse Rostering Competition model

The First International Nurse Rostering Competition has a simple XML format, documented at

<http://www.kuleuven-kortrijk.be/nrpcompetition>

NRConv converts it using models `inrc1.xml` and `inrc1-soln.xml`.

Cover constraints appear as numbers of nurses wanted for each shift, for each skill. NRC demand constraints are not needed. There is a long list of resource constraints. It all maps easily into NRC, except as described now.

`<AlternativeSkillCategory>` defines the penalty to apply when a nurse is assigned to a shift without having the required skill. This allows each nurse to have a different penalty, which is a problem for XESTT, since its prefer resources constraint (the obvious target when converting) associates the penalty with the shift, giving all unqualified nurses the same penalty.

This problem is solved as follows. For each skill s_i and each distinct non-zero weight w_j for `<AlternativeSkillCategory>`, let $S(s_i, w_j)$ be the set of all nurses n such that the assignment of n to a place requiring skill s_i should attract penalty w_j . Let N be the set of all nurses. For each place requiring skill s_i , define one prefer resources constraint for each non-zero weight w_j such that $S(s_i, w_j)$ is non-empty, with weight w_j and set of nurses $N - S(s_i, w_j)$. In practice this produces just one or two prefer resources constraints per skill.

There are instance files (for example, `long01.xml`), which assign skills to nurses whose `<AlternativeSkillCategory>` constraint is turned off. We interpret this to mean that skills defects are to be ignored for those nurses.

`<CompleteWeekends>` requires a nurse to work on each day of the weekend, or none. This is implemented for the first weekend by a cluster busy times constraint with one time group for each day of the weekend, containing the times of that day, and minimum limit equal to the number of days or else 0. For example, if there are two days in the weekend, with five times each day, the constraint has time groups

```
{1Sat1, 1Sat2, 1Sat3, 1Sat4, 1Sat5}
{1Sun1, 1Sun2, 1Sun3, 1Sun4, 1Sun5}
```

and minimum limit 2 or else 0. This is then repeated for each weekend.

When weekends have three or more days, it is possible to work on the first and last days and be free in between them. The competition assigns a higher cost for such cases than for other cases of incomplete weekends. Although several instances do have three-day weekends, NRConv does not implement this refinement. It can be done using unwanted patterns.

`<IdenticalShiftTypesDuringWeekend>` requires a nurse to either work the same shift on each day of the weekend, or to be free on all days. This is expressed for the first weekend by a cluster busy times constraint with one time group for each time of day, containing the weekend's times of that time of day, and maximum limit 1. For example, for the two-day weekend with five times per day, the time groups would be

```
{1Sat1, 1Sun1}
{1Sat2, 1Sun2}
{1Sat3, 1Sun3}
{1Sat4, 1Sun4}
{1Sat5, 1Sun5}
```

This is then repeated for each weekend. Clearly, if shifts of two types are busy during one weekend, two time groups will be active and there will be a violation.

Although this is logically correct, the competition evaluator does more: it treats violations

of `<CompleteWeekends>` as violations of this constraint as well. The cluster busy times constraint just given does not do this.

One possible alternative is a limit busy times constraint with the same time groups as the cluster busy times constraint, but with a minimum limit of 2 or else 0 applied to each. This will penalize the case where (for example) `1Sat1` is busy but `1Sun1` is not, and vice versa. The problem here is that if `1Sat1` and `2Sun4` are both busy, there will be two violations, not one.

The XESTT `Step` cost function could be used to solve this problem, but unfortunately the intermediate model treats the time groups of limit busy times constraints as independent of one another, which they are not when the `Step` cost function is used.

So NRConv generates two constraints for each identical shift types constraint: the cluster busy times constraint, plus the equivalent of a complete weekends constraint. When there is already a complete weekends constraint it merges the two, adding their weights together, provided they have the same hardness and cost function.

`<TwoFreeDaysAfterNightShifts>` requires that on the two days after a night shift, a nurse should either have the day off or else work another night shift. Assuming three shifts per day, with 3 being the night shift, our solution makes patterns `[3][12][12]`, `[3][12][03]`, and `[3][0][12]` unwanted. On the second-last day of the cycle, only `[3][12]` is unwanted.

A violation on both days should cost more than a violation on one, so `[3][12][12]` should get double weight. However, the competition evaluator does not do this, so we assign the same weight to all patterns. We can then merge the first two, producing unwanted patterns `[3][12]` and `[3][0][12]`.

4.4. The Second International Nurse Rostering Competition model

The Second International Nurse Rostering Competition, which is documented at

<http://mobiz.vives.be/inrc2/>

has a similar format to the first, although with fewer resource constraints. NRConv converts it using models `inrc2.xml` and `inrc2-soln.xml`.

The main innovation here is that the competition reflects the way nurse rosters are often made in reality: week by week, not all at once. A *weekly instance* is an instance covering one week; a *global instance* covers several weeks. A global instance is solved by solving a sequence of weekly instances for consecutive weeks. Each is hidden from the solver until it has solved the previous weekly instances.

XESTT has no representation of a sequence of instances connected by history. NRConv produces an XESTT representation of one weekly instance, based on files giving the general scenario, the week in question, and history. It could generate global instances, but one would have to trust the solve for each week to not look ahead. History can be handled by adjusting the limits of the constraints affected, using one constraint per resource. NRConv uses XESTT's history features to generate a single constraint with a history adjustment for each resource, which is clearer and less verbose.

One complication with history concerns the order in which the parts of the source instance are added to the NRC instance. It can be convenient to add constraints before nurses, when

they precede nurses in the source model file. This is done by defining, say, a worker-set for all the nurses of one contract, passing that worker-set to that contract's constraints, and adding the nurses to the worker-set later. But that will not work for constraints affected by history, because they accept history information for individual nurses. Adding the constraints early, then adding their history later would work, but that is painful to organize.

Here is the order used by NRConv:

```

add days (one week's worth), and the one weekend
add shift types
add skills
add contracts
add nurses, including their skills and contracts
add nurse histories to nurses
add worker constraints (shift type, pattern, contract), including history
add cover constraints
add shift-off requests

```

The week file is used only at the end, for cover constraints and shift-off requests. But the scenario file is used out of order, partly to bring everything related to nurses together, but mainly to ensure that nurses are added before constraints, as explained above; and the history file is used in the middle of the scenario file. All this is easy to do because the converter reads all three files and stores them in memory as `KML_ELTT` objects before starting the conversion. What is not so easy, however, is to recognize the dependencies and build the NRC instance in a correct order.

One would think that a Week 0 history file would have zero values for history, but in fact the supplied Week 0 files have many non-zero values. So NRConv fudges and assumes that a Week 0 history file has one week of history.

4.5. The Curtois-Qu 2014 model

Curtois and Qu have recently produced a new set of 24 plain text instances, documented at

<http://www.cs.nott.ac.uk/~psztc/NRP/>

These, and solutions posted by Curtois at the same place, have been converted using source models `cq14.txt` and `cq14-soln.txt`.

Again, much is familiar. Minimum limits on consecutive busy or free days do not apply to sequences that include the first or last day. This is modelled using XESTT's history mechanism in a somewhat artificial manner.

Many resources have a hard limit of 0 on the number of shifts they can take of a given shift type. Although this could be implemented like other workload limits, by a limit workload constraint, we choose instead to build, for each shift type `st`, the set of all workers with a non-zero workload limit for shifts of type `st`, and generate a prefer resources constraint for each shift of type `st` which has this set of workers for its preferred set.

The two approaches are formally equivalent, but the prefer resources constraints allow solvers to reduce the domains of shifts to just those workers who have a non-zero workload for

that kind of shift, and so to avoid attempting assignments which are doomed to fail because of the zero workload limit. This has saved running time in the author's tests of his KHE18 solver.

The solutions to these instances available at the web site above are not the full set reported in Curtois' paper. Accordingly we requested and received a larger set from Curtois.

As in the Curtois original instances, more nurses may be assigned to a shift than the specified optimum, and NRConv creates extra event resources to allow for this. Some of the solutions received from Curtois, especially for the larger instances, overload shifts this way to an unreasonable degree. The worst cases occur in `Instance22.Solution.516686.roster` and `Instance22.Solution.516686_1.roster`, which assign 25 nurses to shift d1 on day 140, when the instance specifies an optimum cover of 1.

We have chosen to generate shifts with maximum cover $2c + 5$, where c is the optimum cover, making solutions that overload shifts beyond that point invalid. Of the 372 solutions received from Curtois, 42 were rejected for this reason. The rest were classified using metadata in the solution files into four solution groups, one for each algorithm in Table 2 of Curtois' paper. The best solution for each instance in each solution group was included in archive CQ14 (66 solutions altogether).